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Saflufenacil efficacy on horseweed and its interaction with glyphosate

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Saflufenacil is a new herbicide on the market and its effectiveness on horseweed, several populations of which have evolved resistance to glyphosate, is not clear. In this research, the effect of adjuvants on the control of horseweed with saflufenacil in the field, the effect of the interaction between glyphosate and saflufenacil on glyphosate-resistant and glyphosate-susceptible horseweed and the patterns of uptake and translocation of glyphosate applied alone and in combination with saflufenacil in horseweed were evaluated. The addition of methylated seed oil to saflufenacil provided the best control of horseweed, with crop oil concentrate being intermediate in effect and non-ionic surfactant ranking as the least-effective adjuvant. The interaction between glyphosate and saflufenacil was additive with regards to the control of glyposate-resistant horseweed. The glyphosate-susceptible horseweed population absorbed 6–13% more ^{14}C-glyphosate than the glyphosate-resistant population. The addition of saflufenacil reduced ^{14}C-glyphosate translocation in both the glyphosate-resistant and the glyphosate-susceptible horseweed populations by at least 6%; however, due to the exceptional efficacy of saflufenacil, these reductions did not reduce the level of control. Saflufenacil holds great potential as an alternative control option for glyphosate-resistant horseweed and is a valuable tool in the management of resistant weeds.

Keywords: *Conyza canadensis*, glyphosate, horseweed, saflufenacil.

Glyphosate is a non-selective, systemic, postemergence herbicide that has been used extensively for controlling many troublesome weeds. The effectiveness of glyphosate as a herbicide, combined with the utility of glyphosate-resistant (GR) crops, has allowed many producers to adopt minimum-tillage and no-tillage practices (Halford *et al.* 2001; Givens *et al.* 2009). Consequently, this widespread adoption has led to an increase in the number of glyphosate applications made during the growing season (Young 2006; Givens *et al.* 2009). The increased use of glyphosate has exerted tremendous selection pressure, resulting in the development of GR weeds. To date, 24 weed species have been reported to be resistant to glyphosate worldwide, including horseweed (*Conyza canadensis*) (Heap 2013).

Horseweed typically has been considered to be a winter annual (Bhowmik & Bekech 1993; Buhler & Owen 1997), but emerges in the spring and summer as well, exhibiting the growth habit of a summer annual (Eubank *et al.* 2006; Davis & Johnson 2008). Given this broad emergence window, GR horseweed has become particularly problematic across much of south-eastern USA. Much of the current research in weed science has been focused primarily on investigating alternative means of control for these developing GR biotypes or populations. Glufosinate controls horseweed well (Steckel *et al.* 2006; Eubank *et al.* 2008), but the level of

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control might be reduced with cooler temperatures at the time of application (Steckel *et al.* 2006; Owen *et al.* 2009). In addition, the size of horseweed at the time of application greatly influences the efficacy of glufosinate. Horseweed control with acetolactate synthase (ALS)-inhibiting herbicides has been effective (Owen *et al.* 2009); however, the widespread development of ALS-resistant horseweed is of concern (Kruger *et al.* 2009; Davis *et al.* 2010). Other possible control options of GR weeds include tank-mixing herbicides with glyphosate. The addition of 2,4-D at 0.84 kg ae ha^{-1} to glyphosate at 0.84 kg ae ha^{-1} increased horseweed control to >95%, compared to 65% with glyphosate alone (Eubank *et al.* 2008). Owen *et al.* (2009) reported that the addition of dicamba at 0.28 kg ae ha^{-1} to glyphosate controlled horseweed by ≤89%. Despite such positive reports, there are limitations as to when phenoxy-type herbicides, such as 2,4-D and dicamba, can be applied prior to planting soybean (*Glycine max*) and cotton (*Gossypium hirsutum*) due to plant-back restrictions and possible crop injury. Compounding the problem is the development of possible phenoxy-resistant horseweed. Kruger *et al.* (2008) reported that some horseweed populations in Indiana exhibited a threefold tolerance to 2,4-D in a greenhouse study. Therefore, alternative control options for the postemergence control of GR horseweed are needed.

Saflufenacil is a new herbicide that has been developed by BASF Corporation and has shown potential as an alternative means of controlling GR horseweed (Bowe *et al.* 2009). Saflufenacil inhibits protoporphyrinogen oxidase activity with a peroxidative mode of action (Grossman *et al.* 2010), leading to the accumulation of protoporphyrin IX (Proto) (Duke *et al.* 1991). Proto is a strong photosensitizer, generating high levels of singlet oxygen in the presence of oxygen and light (Duke *et al.* 1991). These singlet oxygen products lead to the production of hydrogen peroxide, resulting in rapid necrosis and wilting of leaf tissues (Grossman *et al.* 2010). Herbicides that exhibit rapid necrosis of plant tissue can cause the disruption of cell membranes, which in turn, can inhibit the uptake and translocation of other herbicides when applied in combination. Reduced glyphosate absorption that is associated with a combination of contact herbicides with glyphosate has been well documented (Hydrick & Shaw 1994; Starke & Oliver 1998; Norris *et al.* 2001). This poses the question of whether tank-mixing saflufenacil with glyphosate affects the latter's absorption and translocation. In preliminary field studies, a tank mixture of saflufenacil at 0.025 kg ai ha^{-1} and glyphosate at 0.84 kg ha^{-1} controlled GR horseweed by ≤97% (unpublished data). The additive effect that saflufenacil has on glyphosate is unclear. Further research to investigate the uptake and translocation of a systemic herbicide, such as glyphosate, as influenced by saflufenacil, is needed.

The use of adjuvants to increase herbicide efficacy has been well documented (McWhorter & Jordan 1976; Hatzios & Penner 1985; Penner 1989; Wanamarta *et al.* 1989; Nandula *et al.* 2007). The addition of crop oil concentrate (COC) to saflufenacil increased the level of GR horseweed control to 97%, up from the 75% level of control that was obtained with saflufenacil alone (unpublished data). There is little data available on the influence of adjuvants on the efficacy of saflufenacil. Further research is needed to identify the most suitable adjuvant(s) to be used with saflufenacil.

Therefore, the objectives of this research were to: (i) determine the most efficacious adjuvant system for the control of horseweed with saflufenacil; (ii) investigate the effect of the interactions between saflufenacil and glyphosate mixtures on the control of horseweed; and (iii) determine the patterns of uptake and translocation of glyphosate applied alone and in combination with saflufenacil in horseweed.

MATERIALS AND METHODS

Effect of adjuvants

Field studies were conducted in 2008 and 2009 near the Delta Research and Extension Center, Stoneville, MS, USA (33°25′09.16″N and 90°53′09.37″W), to evaluate the effect of adjuvants on the control of horseweed with saflufenacil. The soil type was a Dundee very fine sandy loam (fine-silty, mixed, active, thermic Typic Endoaqualfs) with a pH of 6.1 and organic matter content of 1.2%. The experiments were established following several years of no-tillage GR soybean and were naturally infested with GR horseweed at a density of 30–59 plants per m^2, as recorded in 2008. Confirmation of GR horseweed was conducted in separate greenhouse research (Eubank *et al.* 2012). The treatments were initiated when horseweed reached a growth stage of 10–15 cm in height. The treatments were applied on April 21 2008 and May 5 2008. Saflufenacil (Sharpen 30% WSC; BASF Corporation, Research Triangle Park, NC, USA) was applied at a rate of 0.025 kg ai ha^{-1}. The experimental design was a factorial arrangement of treatments, with one factor being ammonium sulfate (AMS) at 2% w/v or no AMS and the second factor being one of the following adjuvants: no adjuvant, non-ionic surfactant (NIS) (Induce; Helena Chemical Company, Collierville, TN, USA) at 0.25 and 0.5% v/v; COC (Agridex; Helena Chemical Company) at 1 and 2% v/v; and methylated seed oil (MSO) (Helena Chemical Company) at 1 and 2% v/v. An untreated control was

included for comparison. The plot size was 3 m × 12 m and the treatments were applied with a tractor-mounted, compressed-air sprayer that was calibrated to deliver 140 L ha^{-1} using flat-fan nozzles (TeeJet XR 8002EVS flat-fan nozzle; Spraying Systems Company, Wheaton, IL, USA) at a pressure of 210 kPa. The level of horseweed control was estimated visually on a scale of 0 (no control) to 100% (plant death) at 14 and 28 days after treatment (DAT). The treatments had four replications and were repeated in 2009. All the data were subjected to ANOVA, with "experiment" used as a random-effect parameter (SAS 2008). The experiment, replications (nested within experiment) and all the interactions containing these effects were considered to be random effects; the herbicide treatment was considered to be a fixed effect. Considering experiment as an environmental or random effect permits inferences regarding the treatments to be made over a range of environments (Carmer *et al.* 1989). Least square means were calculated and mean separation ($P \leq 0.05$) was applied using PDMIX800 in SAS, which is a macro for converting the mean separation output to letter groupings (Saxton 1998).

Saflufenacil's interactions with glyphosate

Greenhouse studies were conducted in 2009 to evaluate the effect of the addition of glyphosate to saflufenacil on the control of horseweed. Mature seeds from a GR horseweed population were collected from Washington County, MS (33°25′09.16″N and 90°53′09.37″W). The cropping history for the GR population was preceded by at least 5 years of no-till GR soybean. A glyphosate-susceptible (GS) horseweed population from Coahoma County, MS (34°12′07.18″N and 90°32′09.70″W), was selected for comparison. The horseweed seeds (GR and GS) were surface-planted into separate 25 cm × 25 cm × 6 cm trays containing Jiffy mix potting media (Jiffy Products of America Inc., Batavia, IL, USA). The trays were subirrigated with distilled water and placed in a growth chamber at 24/18°C day/night temperatures with supplemental lighting set to a 14 h photoperiod. When the emerged horseweed plants attained at least three true leaves in growth, individual horseweed plants were transplanted to 10 cm pots containing Jiffy potting media. Then, the pots were transferred to a greenhouse with natural light that was supplemented with sodium vapor lamps set to a 14 h photoperiod. The plants were grown at 25/15°C (±3°C) day/night temperatures and subirrigated as needed. The herbicide treatments were initiated on uniform plants with a 10–15 cm rosette diameter, corresponding to ~35–40 leaves per plant.

The herbicide treatments consisted of 0.5X, 1X and 2X rates of glyphosate (Roundup WeatherMAX; Monsanto Company, St. Louis, MO, USA) and saflufenacil applied alone and as a tank mixture. The treatments were glyphosate at 0, 0.42, 0.84 (1X) and 1.68 kg ha^{-1} and saflufenacil at 0, 0.0125, 0.025 (1X) and 0.05 kg ha^{-1}. An untreated control was included for comparison. All the treatments, including the untreated control, included an adjuvant system of AMS at 2% w/v and COC at 1% v/v. The treatments were applied by using an indoor spray chamber equipped with an air-pressurized flat-fan nozzle that was calibrated to deliver a spray volume of 140 L ha^{-1} at a pressure of 220 kPa. The visual ratings for horseweed control were estimated by using a 0–100% scale (0, no control; 100, complete control) at 7, 14 and 21 DAT. The horseweed biomass was collected at 21 DAT by harvesting the plants at the soil line and it was recorded as the fresh weight. The shoot fresh weights were expressed as a percentage of the untreated control for each population.

The experimental design was a randomized complete block with a factorial arrangement of treatments. The factors were "horseweed population" and "herbicide treatment". Each treatment had four replications. A method that was described by Colby *et al.* (1965) was used to calculate the expected response for the herbicide combinations. In order to determine the potential for interaction, the expected and observed values were compared at the 0.05 level of significance using Fisher's Protected Least Significant Difference (LSD) test, calculated for the observed data (Wehtje & Walker 1997; Koger *et al.* 2007). If the observed response of a herbicide combination was either significantly lower or greater than the expected value, the combination was declared "antagonistic" or "synergistic", respectively. Combinations were considered to be additive when the observed and expected responses were similar. All the data were subjected to ANOVA using the general linear model and the means were separated using Fisher's Protected LSD test at the $\alpha = 0.05$ level of significance (SAS 2008).

^{14}C-glyphosate absorption and translocation

Studies were conducted in 2009 to determine the effect of saflufenacil on the absorption and translocation of glyphosate in horseweed. Two horseweed populations, GR and GS, were propagated in the same manner as described previously. When the plants attained a rosette diameter of 4–6 cm, randomly selected individual plants from both populations were treated with glyphosate at 0.11 kg ha^{-1} to establish uniformity (reduced segregation) of resistance and/or susceptibility to glyphosate.

Trial treatments were initiated when the uniformly developed horseweed plants reached 10–15 cm in diameter, corresponding to ~35–40 leaves per plant. Prior to application of the herbicide treatments containing ^{14}C-glyphosate, the youngest, fully expanded leaf was covered with an 8 cm × 8 cm piece of aluminum foil and the plants were over-sprayed with the following treatments: glyphosate at 0.42 kg ha^{-1} alone, glyphosate in combination with1% COC v/v, saflufenacil at 0.0125 kg ha^{-1} and saflufenacil at 0.0125 kg ha^{-1} + COC at 1% v/v. The herbicide rates were 0.5X of the normal field use rates so as to minimize the rapid deleterious effects of glyphosate and saflufenacil on the GS population. Four solutions, similar to the above treatments, but also containing ^{14}C-labeled glyphosate (specific activity: 2.00 GBq mmol^{-1}; 99% purity in an aqueous stock solution of 7.4 MBq mL^{-1} as glyphosate acid) mixed in a commercial formulation of glyphosate to give a final concentration of 0.42 kg in 140 L of water (Reddy 2000), were prepared.

The overspray treatments were applied using an indoor spray chamber, as described previously, and the plants were placed in a growth chamber set at 24/18°C (day/night) with a 14 h photoperiod (300 μmol m^{-2} s^{-1}) that was provided by fluorescent and incandescent bulbs. Within 30 min of the overspray treatments, 10 μL of the respective radioactive solution containing 5KBq ^{14}C-glyphosate was applied with a micro-syringe in the form of 10 1 μL droplets on the adaxial surface of the previously foil-covered leaf. The plants were returned to the growth chamber until harvest. The treated plants were harvested at 24, 48 and 72 h after treatment (HAT). The treated leaf, including the petiole, was excised, immersed in 10 mL of 10% methanol and shaken for 20 s to remove any ^{14}C-glyphosate remaining on the leaf surface. The leaf wash procedure was repeated using a second vial containing 10 mL of 10% methanol. Two 1 mL aliquots from each leaf wash were mixed with 10 mL of scintillation cocktail (EcoLume; ICN Biomedicals, Costa Mesa, CA, USA). The plants were further sectioned into all other leaves, crown and roots. The plant sections were wrapped in tissue paper (Kimwipes EX-L; Kimberly-Clark Corporation, Roswell, GA, USA) and dried at 45°C for 48 h. The oven-dried plant samples were weighed and combusted in a biological oxidizer (Packard Oxidizer 306; Packard Instruments Company, Downers Grove, IL, USA) and the evolved $^{14}CO_2$ was trapped in 10 mL of CarboSorb E (Packard Instruments Company, Meridian, CT, USA) and 10 mL of Permaflour E$^+$ (Packard Instruments Company, Meridian, CT, USA). Radioactivity from the oxidations and leaf wash were quantified by using liquid scintillation spectrometry (Tri-carb 2500TR liquid scintillation analyzer; Packard Bioscience Company, Downers Grove, IL, USA). The total amount of radioactivity that was present in the leaf washes and all the plant sections was considered as the total ^{14}C-glyphosate recovered. The level of recovery of ^{14}C-glyphosate was 98% of the total applied. The sum of radioactivity present in all the plant sections was considered as absorbed and was expressed as a percentage of ^{14}C-glyphosate applied. Translocation was considered to be the sum of all the radioactivity in all the plant sections, except the treated leaf, and was expressed as a percentage of the ^{14}C-glyphosate absorbed. The treatments were arranged in a randomized complete block design. Each treatment was replicated four times and the experiment was repeated. All the data were subjected to ANOVA, using the general linear model in SAS (2008). The means were separated by using Fisher's Protected LSD test at $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Effect of adjuvants on saflufenacil's efficacy

The addition of AMS did not affect the control of horseweed with saflufenacil (data not shown). Hence, the data from the AMS treatments were combined. At 14 DAT, the level of control of horseweed with saflufenacil alone was 78% (Table 1). The highest level of horseweed control (91–93%) at 14 DAT was obtained when saflufenacil was applied with MSO at 1 or 2%. The addition of NIS did not improve the level of horseweed control above the rate of saflufenacil alone. The addition

Table 1. Control of 10–15 cm diameter rosette horseweed at 14 and 28 days after the postemergence treatment with saflufenacil

Treatment†	Rate (%)§	Control (%)	
		14 DAT	28 DAT
No adjuvant		78c‡	71c
Non-ionic surfactant	0.25	78c	72c
	0.50	79c	74c
Crop oil concentrate	1.00	85b	74c
	2.00	86b	81b
Methylated seed oil	1.00	91a	83ab
	2.00	93a	89a

† All the treatments included 0.025 kg ai ha^{-1} saflufenacil; ‡ the means followed by the same letter within each evaluation period are not significantly different at $P < 0.05$; § based on v/v %.
DAT, days after treatment.

of COC to saflufenacil improved the level of control of horseweed compared to no adjuvant, but it was still less than the level of control with MSO. By 28 DAT, the level of horseweed control with saflufenacil was only 71% when no adjuvant was added, which was similar to that obtained with the addition of NIS at either rate or COC at 1%. Crop oil concentrate at 2% increased the level of horseweed control to 81% and was comparable to the 83% control that was obtained with the addition of MSO at 1%, while MSO at 2% with saflufenacil provided the greatest (89%) level of control of horseweed at 28 DAT. These results suggest that the addition of MSO at 2% to saflufenacil should be recommended for the control of 10–15 cm rosette diameter horseweed, which is consistent with the herbicide label (Anonymous 2012). Knezevic *et al.* (2009) reported similar findings where the addition of MSO or COC to saflufenacil improved the control of prickly lettuce (*Lactuca serriola*), field bindweed (*Convolvulus arvensis*), dandelion (*Taraxacum officinale*) and shepherd's-purse (*Capsella bursa-pastoris*) over NIS.

Saflufenacil's interactions with glyphosate

The data are presented separately by population due to significant differences between the GR and GS horseweed populations. At 14 DAT, glyphosate alone at 0.42 kg ha^{-1} gave only 80% control of GS, but the level of control increased to 90% by 21 DAT (Table 2). There was no difference in the level of control of the GS population with glyphosate at either 0.84 or 1.68 kg ha^{-1}, with the level of control being ≥96% at 21 DAT. The level of control of the GR population with glyphosate at 0.42 kg ha^{-1} was 43% at 21 DAT and was not different from the level of control (50%) with glyphosate at 0.84 kg ha^{-1}. Although the level of GR horseweed control increased to 60% at the 1.68 kg ha^{-1} glyphosate rate, this level of control is not commercially acceptable. Saflufenacil alone, irrespective of the rate, controlled the GS population by 95% at 14 DAT and the level of control was 100% by 21 DAT. Similarly, the GR population was controlled by at least 93% at 14 DAT with saflufenacil, while complete control

Table 2. Control of 15 cm diameter rosette glyphosate-susceptible (GS) and glyphosate-resistant (GR) horseweed with postemergence applications of glyphosate alone and in combination with saflufenacil

Treatment†	Rate (kg ha^{-1})‡	GS Control (%)		GR Control (%)	
		14 DAT	21 DAT	14 DAT	21 DAT
Glyphosate	0.420	80	90	40	43
Glyphosate	0.840	87	96	37	50
Glyphosate	1.680	90	100	57	60
Saflufenacil	0.012	95	100	95	100
Saflufenacil	0.025	95	100	93	100
Saflufenacil	0.050	95	100	95	100
Glyphosate + saflufenacil	0.420 + 0.012	93 (99)§	100 (100)	93 (97)	100 (100)
Glyphosate + saflufenacil	0.420 + 0.025	95 (99)	100 (100)	90 (96)	100 (100)
Glyphosate + saflufenacil	0.420 + 0.050	95 (99)	100 (100)	95 (97)	100 (100)
Glyphosate + saflufenacil	0.840 + 0.012	95 (99)	100 (100)	95 (97)	100 (100)
Glyphosate + saflufenacil	0.840 + 0.025	95 (99)	100 (100)	95 (96)	100 (100)
Glyphosate + saflufenacil	0.840 + 0.050	95 (99)	100 (100)	95 (97)	100 (100)
Glyphosate + saflufenacil	1.680 + 0.012	92 (100)	100 (100)	95 (98)	100 (100)
Glyphosate + saflufenacil	1.680 + 0.025	95 (100)	100 (100)	95 (97)	100 (100)
Glyphosate + saflufenacil	1.680 + 0.050	95 (100)	100 (100)	95 (98)	100 (100)
LSD (0.05)¶		5	5	7	7

† All the treatments included 1% v/v crop oil concentrate and 1% w/v ammonium sulphate; ‡ the glyphosate and saflufenacil rates are in ae and ai, respectively; § the expected values are calculated as described by Colby *et al.* (1965) and are enclosed in parentheses; ¶ the interactions were considered to be significant if differences between the observed and the expected control exceeded the appropriate LSD value. DAT, days after treatment; LSD, Least Significant Difference.

occurred at 21 DAT, regardless of saflufenacil's rate. There were no differences between the herbicide rate combinations for horseweed control at 21 DAT, with all the treatments containing saflufenacil and glyphosate providing 100% control of horseweed from both populations. Therefore, all the interactions between glyphosate and saflufenacil were considered to be additive. The control of GR horseweed can be problematic because of the lack of postemergence options for its control. Saflufenacil holds great potential as an alternative means of control for GR horseweed and as a valuable tool in the management of resistant weeds. Saflufenacil also has been listed as a possible alternative control for 2,4-D-resistant prickly lettuce (Burke *et al.* 2009).

^{14}C-glyphosate absorption and translocation

There was no difference in the ^{14}C-glyphosate absorption pattern across the repeated experiments, so the results were combined across trials. The addition of COC did not affect ^{14}C-glyphosate absorption in the glyphosate-alone or in the glyphosate + saflufenacil treatments (data not shown). There were differences in the absorption of ^{14}C-glyphosate between the horseweed populations and the harvest timings for glyphosate alone (Table 3). The GS population absorbed 6–13% more ^{14}C-glyphosate than the GR population, across all harvest times, when treated with glyphosate alone at 0.4 kg ha^{-1}. The level of glyphosate absorption continued to increase over time in both the GS and GR populations, but leveled off in the GS population by 72 HAT. ^{14}C-glyphosate absorption continued to increase in the GR population, but at levels that were lower than the GS population. The addition of saflufenacil increased the level of ^{14}C-glyphosate absorption in the GR population at both 24 and 48 HAT, but not at 72 HAT, compared to glyphosate alone (Table 3). It is hypothesized that the increase in ^{14}C-glyphosate absorption that was observed with the addition of saflufenacil could have been caused by the surfactants and adjuvants that were present in the commercial formulations of glyphosate and saflufenacil. Saflufenacil did not affect ^{14}C-glyphosate absorption in the GS population, compared to glyphosate alone. The glyphosate + saflufenacil-treated leaves from both populations were near complete death by 72 HAT. The greater susceptibility of the GR population to saflufenacil than the GS population might indicate negative cross-resistance, which is defined as greater susceptibility of a resistant population to an alternative mode of herbicide action compared to a susceptible counterpart (Gressel & Segel 1990).

Due to a significant trial effect for ^{14}C-glyphosate translocation, the data are presented separately by trial. There was no difference in the amount of ^{14}C-glyphosate translocation between harvest times for either trial (data not shown). In trial 1, 6–7.1% more ^{14}C-glyphosate translocated out of the treated leaf when treated with glyphosate alone, compared to the treatments containing saflufenacil (Table 4). Similarly, the addition of COC to glyphosate reduced the amount of ^{14}C-glyphosate translocation by 3%. There was no difference in the overall translocation of ^{14}C-glyphosate in the two horseweed populations within trial 1; however, in trial 2, the GS population translocated 2.4% more ^{14}C-glyphosate out of the treated leaf than the GR population (Table 5). The addition of saflufenacil reduced the translocation of glyphosate from 17.2% to 7.5% to 8.4% in the GS population (Table 5). Conversely, there was no difference in glyphosate translocation between the herbicide treatments for the GR population. Overall, the addition of saflufenacil to glyphosate reduced the amount of ^{14}C-glyphosate translocation by 4.6–7.1%, compared to glyphosate alone across trials. Similarly, the addition of COC to

Table 3. ^{14}C-glyphosate absorption in glyphosate-resistant (GR) and glyphosate-susceptible (GS) horseweed treated with glyphosate alone at 0.4 kg ae ha^{-1} or in combination with saflufenacil at 0.0125 kg ai ha^{-1}

Population	Treatment	Rate (kg ha^{-1})	^{14}C-glyphosate absorption (% of applied)		
			24 HAT	48 HAT	72 HAT
GR	Glyphosate	0.4	32	36	44
GS	Glyphosate	0.4	44	49	50
GR	Glyphosate + saflufenacil	0.4 + 0.0125	38	44	39
GS	Glyphosate + saflufenacil	0.4 + 0.0125	45	45	52
LSD (0.05)			6	6	6

HAT, hours after treatment; LSD, Least Significant Difference.

Table 4. ^{14}C-glyphosate translocation and distribution in glyphosate-resistant (GR) and glyphosate-susceptible (GS) horseweed, as influenced by saflufenacil, averaged across 24, 48 and 72 h after treatment (trial 1)

Population	Treatment†	^{14}C-glyphosate distribution (% of absorbed)				
		Translocation‡	Treated leaf	Crown	Other leaves	Roots
GR	A	10.1	89.9	4.8	1.2	4.1
	B	8.6	91.4	4.6	0.7	3.3
	C	5.0	95.0	3.3	0.4	1.3
	D	6.1	93.9	2.7	0.8	2.6
GS	A	13.2	86.8	10.3	2.3	0.6
	B	8.0	92.0	6.5	1.2	0.3
	C	3.8	96.2	2.8	0.8	0.2
	D	5.0	95.0	3.6	0.9	0.5
LSD (0.05)		NS	NS	2.1	NS	NS
GR	–	7.4	92.6	3.8	0.8	2.8
GS	–	7.5	92.5	5.8	1.3	0.4
LSD (0.05)		NS	NS	1.1	0.4	0.9
–	A	11.5	88.5	7.5	1.7	2.3
–	B	8.2	91.8	5.5	0.9	1.8
–	C	4.4	95.6	3.0	0.6	0.8
–	D	5.5	94.5	3.1	0.9	1.5
LSD (0.05)		2.0	2.0	1.5	0.5	NS

† Treatments: A, 0.42 kg ae ha^{-1} glyphosate alone; B, 0.42 kg ae ha^{-1} glyphosate + 1% v/v COC; C, 0.42 kg ae ha^{-1} glyphosate + 0.125 kg ai ha^{-1} saflufenacil; D, 0.42 kg ae ha^{-1} glyphosate + 0.125 kg ai ha^{-1} saflufenacil + 1% v/v COC; ‡ ^{14}C-glyphosate outside of the treated leaf (other leaves, crown and roots) is considered as translocation from trial 1. COC, crop oil concentrate; LSD, Least Significant Difference; NS, not significant.

glyphosate alone reduced the level of translocation by 3.3–3.4%. This decrease in translocation probably was related to the deleterious effects of saflufenacil on plant processes, limiting ^{14}C-glyphosate movement within the plant. There was no difference in the translocation of ^{14}C-glyphosate across the saflufenacil-treated plants, regardless of the population or HAT in trial 2 (Table 5). These data highlight the negative effects that saflufenacil and COC have on the translocation of ^{14}C-glyphosate in susceptible horseweed. These findings are similar to those of Steele *et al.* (2008), where diuron reduced the level of translocation of ^{14}C-glyphosate in sharppod morningglory (*Ipomoea cordatotriloba*).

Approximately 6% more ^{14}C-glyphosate moved into the crown of GS with glyphosate alone, compared to GR in trial 1 (Table 4). The addition of COC reduced the movement of ^{14}C-glyphosate into the crown of GS by nearly 4%, compared to glyphosate alone, whereas the addition of saflufenacil reduced the levels by 7–8%. Within both trials, there was no difference in the accumulation of ^{14}C-glyphosate within the crown of the GR plants between the treatments and it was comparable to the ^{14}C-glyphosate levels in the crown leaves of the saflufenacil-treated GS population (Tables 4 and 5). Nearly 9% more ^{14}C-glyphosate moved into the crown of the GS plants that were treated with glyphosate alone, compared to the GR population (Table 5). The addition of COC to glyphosate reduced the level of translocation of ^{14}C-glyphosate by 6% in GS, compared to glyphosate alone, as in trial 1. Within the GS population, the addition of saflufenacil further reduced ^{14}C-glyphosate translocation, compared to glyphosate alone and glyphosate + COC (Table 5).

There was no difference in the distribution of ^{14}C-glyphosate in the other leaves when the data were separated by population and by treatment (Tables 4 and 5). However, when averaged across treatments or populations, certain trends in ^{14}C-glyphosate movement to other leaves were apparent in both trials. For instance, the GS population translocated 1.3% of the absorbed $_{14}$C-glyphosate into other leaves, compared to GR at 0.8% in trial 1 (Table 4). These findings were nearly identical to those for trial 2, where the GS plants translocated 0.7% more ^{14}C-glyphosate compared to the GR plants (Table 5). Similar results were reported by Feng *et al.* (2004), where more glyphosate was moved to other leaves in the susceptible, compared to the resistant, population. Among treatments, averaged across

Table 5. ^{14}C-glyphosate translocation and distribution in glyphosate-resistant (GR) and glyphosate-susceptible (GS) horseweed, as influenced by saflufenacil, averaged across 24, 48 and 72 h after treatment (trial 2)

Population	Treatment†	Translocation‡	^{14}C-glyphosate distribution (% of absorbed)			
			Treated leaf	Crown	Other leaves	Roots
GR	A	9.4	90.6	5.7	1.0	2.7
	B	9.0	91.0	5.4	1.3	2.3
	C	8.9	91.1	5.2	1.4	2.3
	D	7.1	92.9	3.8	0.8	2.5
GS	A	17.2	82.8	14.6	2.0	0.6
	B	10.6	89.4	8.6	1.7	0.3
	C	8.4	91.6	6.0	1.7	0.7
	D	7.5	92.5	4.9	1.8	0.8
LSD (0.05)		3.0	3.0	2.4	NS	NS
GR	–	8.5	91.5	5.0	1.1	2.4
GS	–	10.9	89.1	8.5	1.8	0.6
LSD (0.05)		2.0	2.0	1.2	0.4	0.6
–	A	13.2	86.8	10.1	1.5	1.6
–	B	9.8	90.2	7.0	1.5	1.3
–	C	8.6	91.4	5.6	1.5	1.5
–	D	7.3	92.7	4.3	1.3	1.7
LSD (0.05)		2.0	2.0	1.7	NS	NS

† Treatments: A, 0.42 kg ae ha^{-1} glyphosate alone; B, 0.42 kg ae ha^{-1} glyphosate + 1% v/v COC; C, 0.42 kg ae ha^{-1} glyphosate + 0.125 kg ai ha^{-1} saflufenacil; D, 0.42 kg ae ha^{-1} glyphosate + 0.125 kg ai ha^{-1} saflufenacil + 1% v/v COC; ‡ ^{14}C-glyphosate outside of the treated leaf (other leaves, crown and roots) is considered as translocation from trial 2. COC, crop oil concentrate; LSD, Least Significant Difference; NS, not significant.

populations (and harvest time), more ^{14}C-glyphosate translocated to other leaves when the plants were treated with glyphosate alone, compared to the addition of COC and/or saflufenacil in trial 1 (Table 4). In trial 2, the distribution of ^{14}C-glyphosate in other leaves was similar between treatments (Table 5).

The distribution of ^{14}C-glyphosate in the roots was not affected by the herbicide treatment within either trial, but there were differences between the horseweed populations. The GR population translocated 2% more ^{14}C-glyphosate to the roots than did the GS population (Tables 4 and 5). These data conflict with earlier findings (Koger & Reddy 2005), where more ^{14}C-glyphosate was translocated to the roots in the susceptible horseweed population than in the resistant one. This study did not investigate the presence or absence of a sequestration mechanism (Ge *et al*. 2010), where glyphosate is moved away from the site of action within meristematic tissues of the crown and into vacuoles in the resistant population.

In summary, the addition of saflufenacil reduced the amount of ^{14}C-glyphosate translocation in both the GR and the GS horseweed populations by at least 6% across experiments. However, due to the exceptional efficacy of saflufenacil on horseweed, it is possible that this would have no negative effect on horseweed control in the field. Additionally, this research suggests that the addition of COC to glyphosate reduces the translocation of glyphosate in horseweed into other plant parts. Nandula *et al*. (2007) advised against adding COC to glyphosate spray mixtures due to possible antagonism. Current labeling for saflufenacil recommends the addition of 1% v/v COC or MSO. Tank mixtures of saflufenacil and glyphosate probably will be used by producers in order to improve the level of control of many broad-leaved weed species. Additional research might be needed to determine if saflufenacil will have similar reductions in the translocation of glyphosate in other broad-leaved species. Saflufenacil holds great potential as an alternative control option for GR horseweed and as a valuable tool in the management of resistant weeds.

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