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Trifludimoxazin Mixtures for Preplant Burndown Weed Control in Soybean

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Abstract

Trifludimoxazin is a novel protoporphyrinogen oxidase (PPO)-inhibiting herbicide currently under development for foliar and residual control of several problematic weeds in preplant applications for soybean production. Field experiments were conducted in 2017 and 2018 to evaluate the foliar efficacy of trifludimoxazin applied alone and in combination with other herbicides on waterhemp, giant ragweed, and horseweed. Foliar applications of trifludimoxazin alone at 12.5 or 25 g ai ha^{-1} were highly efficacious on glyphosate-resistant waterhemp (94 to 99% control, respectively), moderately effective on giant ragweed (78 to 79% control, respectively), and resulted in minor efficacy on horseweed (≤ 20% control). Combinations of trifludimoxazin with glufosinate, glyphosate, paraquat, or saflufenacil remained highly effective (≥ 91% control) on waterhemp and giant ragweed. All herbicide mixtures with trifludimoxazin applied to horseweed were classified as additive interactions. Greenhouse experiments and Isobole analysis indicated trifludimoxazin mixtures with glyphosate and glufosinate on waterhemp and giant ragweed were additive. Mixtures of trifludimoxazin plus paraquat were slightly antagonistic under greenhouse conditions when applied to either waterhemp or giant ragweed, whereas trifludimoxazin plus saflufenacil was synergistic when applied to giant ragweed. Overall, trifludimoxazin applied alone at 12.5 or 25 g ha^{-1} was effective for managing waterhemp, and to an extent, giant ragweed, but not horseweed in preplant burndown applications. Furthermore, the addition of glufosinate, glyphosate, paraquat, or saflufenacil to applications of trifludimoxazin does not appreciably reduce weed control for these mixtures. As such, applications of trifludimoxazin alone and in combination with these herbicides may be utilized for effective preplant management of several problematic weeds in soybean.

Nomenclature: glufosinate; glyphosate; paraquat; saflufenacil; trifludimoxazin; giant ragweed, *Ambrosia trifida* L.; horseweed, *Erigeron canadensis* L. Cronq.; waterhemp, *Amaranthus tuberculatus* (Moq.) Sauer;

Keywords: additivity; antagonism; synergism;

Introduction

In Indiana, waterhemp, giant ragweed, and horseweed are among the most problematic weeds in soybean production (Gibson et al. 2005). In the eastern Corn Belt, giant ragweed and waterhemp emergence can begin in mid-March and mid-April, respectively, and continues throughout much of the soybean growing season (Heneghan 2016; Johnson et al. 2007). Horseweed, in contrast, can grow as a winter annual or summer annual, and is capable of germination and emergence almost year-round, depending on geography (Buhler and Owen 1997). Soybean yield loss resulting from weed competition varies by species, but season-long interference has been documented to reduce soybean grain yields by 56% with waterhemp, 77% with giant ragweed, and as much as 90% with horseweed (Bensch et al. 2003; Bruce and Kells 1990; Webster et al. 1994). As a result, effective management approaches are necessary to minimize crop yield loss resulting from competition from these weeds.

Effective weed management often begins with planting crops into weed-free fields. While tillage has historically been an effective means for reducing competition from winter annuals and early germinating summer annual weeds, adoption of reduced- or no-till practices predominates, with approximately 70% of US soybean producers implementing some manner of conservation tillage (Claassen et al. 2018). A reduction in tillage intensity can facilitate increased diversity among weeds that are present (Murphy et al. 2006), and non-selective herbicides for preplant weed management in soybean has become commonplace (Lanie et al. 1994). Historically, glyphosate has been the most common non-selective herbicide used for preplant vegetation management; however, glyphosate resistance has been problematic in a number of species, including glyphosate-resistant waterhemp, giant ragweed and horseweed in Indiana (Davis et al. 2008; Givens et al. 2009; Harre et al. 2017; Heap 2024). The challenge in managing these herbicide-resistant weeds has led to the use of other non-selective herbicides, such as paraquat and glufosinate, to manage resistant weed biotypes (Eubank et al. 2008). In addition to diversification of herbicides used, mixtures of herbicides can be implemented to improve the spectrum of weeds controlled. This practice is especially useful when using selective herbicides like 2,4-D, dicamba, or saflufenacil, particularly when glyphosate-resistant weeds are present (Eubank et al. 2013; Robinson et al. 2012; Spaunhorst and Bradley 2013).

The efficacy of these herbicide mixtures is paramount, as a variety of outcomes regarding plant response are possible following their co-application. Specifically, the three most common responses are synergy, additivity, and antagonism (Colby 1967). For weed control, additivity and synergy are both desirable outcomes, as plant response following the co-application of multiple herbicides is equal to or greater than the expected response of each herbicide applied independently (Flint et al. 1988). Utilizing additive or synergistic mixtures can improve the spectrum of weeds controlled, while simultaneously reducing time and monetary inputs associated with multiple successive herbicide applications (Hatzios and Penner 1985). Moreover, synergistic combinations are particularly beneficial to provide high levels of weed control with reduced herbicide rates, as well as improve control of herbicide-resistant weed biotypes (Walsh et al. 2012). Conversely, reductions in herbicide efficacy because of antagonism between two co-applied herbicides can result in a failed herbicide application. Optimizing herbicide use patterns to control herbicide-resistant weeds has arguably never been more important, as there are over 500 unique cases of herbicide resistance encompassing over 270 species and 21 herbicide modes of action (MOA) (Heap 2024).

Trifludimoxazin is a novel protoporphyrinogen oxidase (PPO)-inhibiting herbicide currently under development for preplant applications in a number of crops including soybean, corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.) (Asher et al. 2020; Findley et al. 2020). Previous reports have indicated that trifludimoxazin may be applied either alone, or in combination with other herbicides, for broad-spectrum control of several problematic weed species, including those that are resistant to commercial PPO inhibitors (Findley et al. 2020). Scientific literature is depleted on the efficacy of trifludimoxazin alone or in mixture with other standard herbicides used in preplant applications. Therefore, our objectives were to: 1) determine the efficacy of foliar applications of trifludimoxazin compared with glufosinate, glyphosate, paraquat, and saflufenacil; and 2) investigate potential mixture interactions between trifludimoxazin and the other four herbicides, when applied to waterhemp, giant ragweed, or horseweed.

Materials and Methods

Field Efficacy

Three field experiments were conducted in 2017 and 2018 utilizing foliar applications of trifludimoxazin alone (12.5 or 50 g ai ha^{-1}), and in combination with glyphosate (870 g ae ha^{-1}), glufosinate (590 g ai ha^{-1}), paraquat (840 g ai ha^{-1}), or saflufenacil (25 g ai ha^{-1}), on waterhemp,

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giant ragweed, and horseweed. Information regarding herbicide manufacturers for products used can be found in Table 1. Experiments were established in fallow field areas at locations with endemic near-monocultures of each target weed species. Waterhemp and horseweed experiments were conducted near Brookston, Indiana (40.58°N, 86.77°W), with native populations of both species having high levels of resistance to glyphosate. Giant ragweed experiments were conducted at the Throckmorton Purdue Agriculture Center, near Lafayette, Indiana (40.29°N, 86.90°W). Experiments implemented plots measuring 3- by 9-m, arranged in a randomized complete block design (RCBD) with four replications.

Herbicide treatments were applied using a CO_2-pressured backpack sprayer with a 2-m handheld spray boom equipped with four flat-fan XR8002 spray tips (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 276kPa. In addition to the aforementioned herbicides, methylated seed oil (MSO Ultra, Precision Laboratories, Waukegan, IL) and ammonium sulfate (N-Pak AMS Liquid, Winfield Solutions, St. Paul, MN) were added to each treatment at 1% v/v and 1% w/w, respectively, as both are either required or permitted for the labeled use of each product. Relatively large weeds were targeted for each species in an effort to elicit sub-lethal response in weeds, as applications of individual herbicides resulting in approximately 50% control are most useful for analyzing herbicide interactions (Colby 1967; Meyer and Norsworthy 2019). Applications were performed when average weed height was 15- to 20-cm for waterhemp and 20- to 25-cm for giant ragweed and horseweed. Four randomly selected plants within each plot measuring 18-cm (waterhemp) or 23-cm (giant ragweed and horseweed) were marked at the time of application for further evaluation. Average densities of waterhemp, giant ragweed, and horseweed were 450, 100, and 400 plants m^2, respectively. Due to the high weed density within plots, vegetation immediately surrounding the marked plants was manually removed prior to application to facilitate adequate herbicide coverage on marked plants during application, and to reduce localized competition after application. Visual estimates of control for whole plots, in addition to marked plants within each plot, were assessed at 3, 7, 14, and 21 or 28 days after application (DAA) using a 0 (no control) to 100 (complete plant death) scale. Waterhemp and horseweed experiments were terminated at 28 DAA, but data collection for giant ragweed experiments was concluded at 21 DAA due to high levels of biomass accumulation in non-treated plots at that timing. Following the final visual evaluation, plant height was recorded in the marked plants within each plot, and aboveground biomass collected by clipping the plants at the soil surface. Plants harvested for biomass evaluation were oven-dried at 60 C for 7 d, then weighed. Both height and biomass data were converted to a relative percentage of the height or weight from the non-treated plot within each replicate.

Visual estimates of control and height/biomass reduction data were subjected to analysis of variance (ANOVA) using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC) and significant means separated using Tukey's HSD (α = 0.05). Herbicide treatment was considered a fixed effect, whereas year and replication were treated as random effects. Data were analyzed separately by species and combined over years as a result of non-significant treatment by year interaction within species. Colby's method was used to evaluate interactions between trifludimoxazin and the other four herbicides for the data collected at the final evaluation timing. Assessment via Colby's method requires the calculation of expected control values for combinations of herbicides using Equation 1:

$$E = (X + Y) - [\frac{(XY)}{100}] \quad [1]$$

where E is the expected level of control when two herbicides are applied in mixture, and X and Y represent the control observed from each herbicide applied individually. Control values observed for mixtures in the field were compared with the calculated expected values via a two-sided t-test (α = 0.05), where a significant deviation of the observed value from the expected value indicates either synergism or antagonism (Lancaster et al. 2019; Walsh et al. 2012).

Greenhouse Isobole Analysis

Greenhouse experiments were conducted to further characterize the interaction of trifludimoxazin and glufosinate, glyphosate, paraquat, or saflufenacil on waterhemp and giant ragweed, using the Isobole method (Berenbaum 1989; Akobundu et al. 1975; Tammes 1964). In general, Colby's method for analysis of herbicide interactions is appropriate for field research where the number of treatments can be limited, whereas the Isobole method provides a more complete analysis of the herbicide interaction across a more robust response range. However, the Isobole method requires preliminary herbicide dose response experiments and large sets of herbicide dose interactions which may only be reasonable with the smaller experimental units found in controlled environment experiments.

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Isobole methodology was adapted from Armel et al. (2007), which utilized a concentration addition (CA) joint action reference model (Abendroth et al. 2011; Cedergreen et al. 2008; Cedergreen 2014) to create isobolograms predicting the efficacy of herbicide combinations based on the relative potencies of their component parts. This iteration of the Isobole method assumes the efficacy of a mixture of two herbicides, at a fixed ratio (based on relative potency), is equal to the efficacy of the individual components, unless the herbicides are acting antagonistically or synergistically. In order to assess potential antagonistic or synergistic interactions with this method, several doses of each herbicide are applied alone, and the rate required for each herbicide to elicit a 50% response level (GR_{50} value) was calculated. The GR_{50} values were plotted on an x-y coordinate graph, and an "independent action line" was created by connecting the values for each herbicide. The independent action line indicates the infinite combination of doses of each of the herbicides that should provide a 50% response for additive interactions. Additionally, herbicide combinations were applied at fixed ratios based on the relative potencies of the individual components of the mixture, as determined by preliminary experiments (Armel et al. 2007).

Preliminary dose response assays were conducted to determine the relative potency of each herbicide evaluated compared with trifludimoxazin using five rates of each herbicide. Data were subjected to non-linear regression using a four-parameter log-logistic model (Equation 2):

$$f(x) = c + \frac{d-c}{1+\exp\,(b(\log(x)-\log\,(e)))} \qquad [2]$$

where *b* is the slope of the curve, *c* is the lower asymptote, *d* is the upper asymptote, and *e* is the GR_{50} value, via the *drc* package in R software v. 3.6.2 (Knezevic et. al 2007). GR_{50} values from glufosinate, glyphosate, paraquat, and saflufenacil were compared with trifludimoxazin to elucidate the relative potency of each herbicide (Table 2) and rate structures for subsequent interaction experiments were based on the calculated potencies.

Seeds from a waterhemp population, susceptible to both glyphosate and PPO-inhibitors, were sown in 25- by 50-cm greenhouse flats containing commercial potting mix (Fafard Germinating Mix; Sun Gro Horticulture, Agawa, MA). Seedlings were transplanted to 164-cm^3 cone-tainers (Ray Leach SC-10 Super Cell Cone-tainers; Stuewe & Sons, Tangent, OR), filled with a 2:1 mixture of potting soil and sand, when seedlings reached the one-leaf stage, and allowed to grow until the 4- to 6-leaf stage (6cm average height). Giant ragweed seeds were stratified in a 3:1 mixture of sand to soil for 4 wk following methodology described by

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Westhoven et al. (2008) to alleviate dormancy. After a 4-wk stratification, seeds were sown in greenhouse flats containing commercial potting mix, similar to waterhemp. Following germination and expansion of cotyledons, seedlings were transplanted to square 10- by 10-cm pots filled with a 2:1 mixture of potting soil and sand. Seedlings were allowed to grow until four true leaves were fully expanded (6 cm average height), at which point herbicide applications were made. Both waterhemp and giant ragweed were watered daily and fertilized weekly using a micro- and macronutrient fertilizer (Jack's Classic Professional 20-20-20, JR Peters Inc., Allentown PA) throughout the course of the experiments.

Herbicide applications were made using a track-mounted research sprayer (Generation III Research Sprayer, DeVries Manufacturing, Hollandale MN) calibrated to deliver 140 L ha^{-1} at 207 kPa with an even flat fan XR8002E (TeeJet Technologies, Glendale Heights, IL) spray tip. For waterhemp experiments, six rates of trifludimoxazin (0 to 1.6 g), glufosinate (0 to 32 g), glyphosate (0 to 480 g), paraquat (0 to 48 g), and saflufenacil (0 to 1.2 g) were applied alone and in combinations of each herbicide based on the relative potency of each herbicide (Table 2). In giant ragweed experiments, trifludimoxazin (0 to 13.5 g), glufosinate (0 to 473 g), glyphosate (0 to 878 g), paraquat (0 to 405 g), and saflufenacil (0 to 4.05 g) plus combinations were performed. All herbicide treatments included methylated seed oil (MSO Ultra, Precision Laboratories, Waukegan, IL) and ammonium sulfate (N-Pak AMS Liquid, Winfield Solutions, St. Paul, MN) 1% v/v and 1% w/w, respectively.

Experiments were conducted utilizing a two-factor (herbicide x rate) factorial, RCBD, with ten replications, and repeated once for each species. Visual estimates of control were made at 3, 7 and 14 DAA utilizing a 0 to 100 scale, as described previously. At 14 DAA, aboveground biomass was collected by clipping plants at the soil surface. Collected plant tissue was oven-dried for 7 d at 60C, and data were normalized according to the non-treated check within each species/herbicide combination. Biomass data were analyzed via four-parameter log-logistic regression using Equation 2 to calculate GR_{50} values for each herbicide or herbicide combination (Table 3), with data pooled over runs due to a lack of treatment by run interaction, as determined by ANOVA ($\alpha = 0.05$). Isobolograms were created, as previously described, using the GR_{50} values for individual herbicides to create a line of independent action for each herbicide combination. Calculated GR_{50} values, along with 95% confidence intervals, for herbicide combinations were partitioned proportionally into each component part according to the relative rates of each herbicide used within a mixture. These values were then plotted on the same graph as the independent action line for each herbicide combination within species. Interactions were classified based on the relative position of the GR_{50} values for herbicide combinations in comparison with the independent action line, where antagonism was indicated by a value above the line, synergy below the line, and additivity when the value did not deviate from the line.

Results and Discussion

Waterhemp

Trends in control of marked plants reflected observations on the whole plot level, with, generally speaking, higher control in marked plants relative to the whole plot. Lower control on the whole plot level can likely be attributed to reduced herbicide coverage as a result of the high weed density and plant height at application. Marked plants were more uniform in height at herbicide application, relative to plants across the entire plot, and were used to determine biomass and height reductions compared with non-treated checks. While both whole plot data and marked plant data are presented, discussion herein pertains only to marked plant data.

Foliar applications of trifludimoxazin alone in the field translated to rapid and near complete control of waterhemp with a high frequency of glyphosate-resistant individuals within the population. By 3 DAA, control of marked waterhemp plants was 95% and 96% control for trifludimoxazin applied at 12.5 and 25.0 g ha^{-1}, respectively (Table 4). The rapid onset of observed symptomology was similar to the quick-acting contact activity displayed in treatments containing saflufenacil or paraquat, where control on marked plants was 89% and 97%, respectively, at 3 DAA (Table 4). In contrast, applications of glufosinate (32%) and glyphosate (5%) were in the early stages of symptom development at 3 DAA. At later evaluation timings, similar trends were observed, with applications of trifludimoxazin and paraquat providing 94% to 100% control of marked plants 28 DAA (Table 4). Waterhemp regrowth following saflufenacil treatment was observed over the course of the experiment, ultimately resulting in less control (81%) at 28 DAA than the peak activity at 3 DAA (Table 4). Applications of glufosinate resulted in low levels (36%) of waterhemp control at 28 DAA, consistent with previous research that has demonstrated reduced glufosinate efficacy in relatively taller weeds like those targeted in the present study (Barnett et al. 2013; Steckel et al. 1997). As anticipated, applications of glyphosate alone remained the least effective herbicide treatment for the

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glyphosate-resistant population evaluated in this experiment, providing 12% control of marked waterhemp plants at 28 DAA.

Although waterhemp control under field conditions exceeded 91% for all combinations of trifludimoxazin plus glufosinate, glyphosate, paraquat, or saflufenacil, several instances of antagonism occurred according to Colby's analysis (Table 5). Specifically, trifludimoxazin plus glyphosate mixtures only exhibited an additive response, while all other combinations produced at least one instance of antagonism. These observations may practically be classified as "false antagonism", as described by Hugie et al. (2008), where the authors note that high levels of control imparted by applications of one or both components of a mixture arithmetically limit the utility of Colby's method, such that a "less than additive" (i.e. antagonistic) response is the only possibility.

Greenhouse experiments utilizing the Isobole analysis method demonstrated an additive effect for the trifludimoxazin combinations on waterhemp (Figure 1). The only exception was the combination of trifludimoxazin plus paraquat, which was slightly antagonistic. The contrast between mixture interactions observed in several combinations from field and greenhouse experiments highlights the impact of herbicide rate selection and weed size at application, among other factors, which can influence the characterization of these interactions (Green 1989; Riley and Shaw 1988; Scott et al. 1998).

When considering results from both field and greenhouse experiments, trifludimoxazin applied at 12.5 or 25 g ha^{-1} appears to be an effective option for management of waterhemp, even when applied to plants as large as 15- to 20-cm. Additionally, although some combinations of trifludimoxazin plus field use rates of glufosinate, paraquat, or saflufenacil, were deemed antagonistic under field and greenhouse conditions, high levels of control were still attained in the field. Thus, trifludimoxazin combinations evaluated may still provide substantial utility for managing waterhemp, especially where glyphosate-resistant populations are present. Combinations of other PPO-inhibitors with systemic herbicides, like glyphosate, can be either synergistic or antagonistic, depending on the weed species and biotype, herbicide, or rates applied (Ashigh and Hall 2010; Norris et al. 2001). One example, presented by Mellendorf et al. (2013), showed that the addition of glyphosate to saflufenacil increased control of a glyphosate-resistant population of horseweed when lower rates of saflufenacil were applied. While the same did not hold true following applications of higher rates of saflufenacil with glyphosate, the efficacy of saflufenacil was not reduced as a result of adding glyphosate. In our results, the addition of glyphosate to trifludimoxazin similarly did not compromise the high efficacy of applications of trifludimoxazin alone. While little information exists regarding interactions between PPO inhibitors and other contact herbicides, a recent study found that applications of reduced rates of glufosinate and lactofen or saflufenacil were synergistic when applied to waterhemp (Takano et al. 2020). Although synergy was not observed between trifludimoxazin and glufosinate using full use rates of either herbicide under field conditions, or with constant rates consistent with the relative potency of each herbicide in the greenhouse, altering the ratios of each herbicide applied in mixture may possibly result in synergism.

Giant Ragweed

Similar to results from waterhemp field experiments, the onset of trifludimoxazin activity was rapid in giant ragweed with applications of 12.5 and 25 g ha^{-1} resulting in 83% and 85% control 3 DAA on marked plants (Table 6). Necrotic symptomology following trifludimoxazin applications peaked at the 7 DAA evaluation timing, with a decline in control observed at the later evaluation timings as a result of regrowth from apical and axillary meristems (Table 6). By 21 DAA, all herbicide treatments, with the exception of trifludimoxazin or glyphosate alone, resulted in near complete control (≥ 99%) of marked plants (Table 6). While analysis of height reduction via Colby's method indicated all but one herbicide combination to be antagonistic (data not shown), these observations may again be best classified as false antagonism due to the high levels of height reduction imparted by applications of the individual herbicides. When considering visual estimates of control and biomass reduction data, additive interactions predominated for herbicide combinations with trifludimoxazin on giant ragweed. Indeed, the only interaction that was not additive was the synergistic combination of trifludimoxazin at 25 g ha^{-1} applied with glyphosate (Table 7).

Combinations of trifludimoxazin and glufosinate or glyphosate in the greenhouse were additive on giant ragweed, while mixtures with paraquat or saflufenacil were antagonistic and synergistic, respectively (Figure 2). An interesting contrast exists between field and greenhouse results, with trifludimoxazin plus paraquat proving to be antagonistic when applied at sub-lethal rates to both smaller giant ragweed and waterhemp plants, yet high levels of efficacy were still observed when applied to large plants at field-use rates. Green (1989) states that "antagonism defines a type of herbicide interaction, not whether a mixture is agronomically useful". This highlights the importance of considering the practical implications of calculated antagonism in the context of how herbicide mixtures will be applied under field conditions. In our research, even though antagonistic relationships have been observed, the combination of trifludimoxazin with the four herbicides on giant ragweed appear to still result in successful weed control when applied at field use rates. Conversely, the synergy observed between trifludimoxazin and saflufenacil under greenhouse conditions implies that varying the rates of each herbicide in combination may have practical relevance in terms of giant ragweed control. Future research investigating different ratios of trifludimoxazin plus saflufenacil may help elucidate the synergistic interaction between these two herbicides.

Horseweed

Field applications of trifludimoxazin alone were ineffective on horseweed, providing ≤ 20% control regardless of herbicide rate or evaluation timing (Table 8). At 28 DAA, applications of trifludimoxazin resulted in ≤ 10% control of marked horseweed plants, which was similar to efficacy applications of glyphosate alone (17%), or mixtures of trifludimoxazin plus glyphosate (17% to 29%) (Table 8). Conversely, treatments containing glufosinate, paraquat, saflufenacil, or combinations of trifludimoxazin plus any of these herbicides, were highly efficacious, providing ≥ 91% control of marked horseweed plants 28 DAA (Table 8). Due to negligible activity of trifludimoxazin, and an absence of interactions, save for additivity, between the other herbicides investigated, subsequent greenhouse experiments were not conducted for horseweed.

These results indicate that the foliar activity of applications of trifludimoxazin alone on horseweed is much lower when compared with saflufenacil, which is an effective herbicide for horseweed management (Mellendorf et al. 2013). Rather, the efficacy of trifludimoxazin more closely resembles that of other PPO-inhibiting herbicides like carfentrazone or flumioxazin, which are efficacious when applied to *Amaranthus* weeds, but have low activity when foliar applications are made to horseweed (Davis et al. 2010; Shrestha et al. 2008, Tahmasebi et al. 2018). Thus, applications of trifludimoxazin alone will not be a viable option for controlling horseweed. Alternatively, since the addition of trifludimoxazin did not reduce the high levels of efficacy observed following applications of glufosinate, paraquat, or saflufenacil, mixtures of

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trifludimoxazin with these herbicides may be utilized for effective management of horseweed, including glyphosate-resistant biotypes like those evaluated in field studies herein.

Practical Implications

This study concludes that foliar applications of trifludimoxazin are effective for managing waterhemp (including glyphosate-resistant populations), and to some extent giant ragweed, but not horseweed. Mixtures of trifludimoxazin with any of the herbicides evaluated resulted in high levels of weed control for all three species under field conditions, except for trifludimoxazin plus glyphosate applied to glyphosate-resistant horseweed. Where glyphosate-resistant horseweed is present, effective control can still be achieved with combinations of trifludimoxazin plus glufosinate, paraquat, or saflufenacil. As such, preplant burndown applications of trifludimoxazin alone and in combination with these herbicides will be an effective management tool for several problematic weeds in soybean, and the utility of these herbicides will be especially relevant where emerged weeds exist prior to soybean planting (e.g. double-crop soybeans, delayed planting situations, and in southern latitudes where weed germination begins earlier in the season).

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Competing Interests

Author N.R. Steppig is currently employed by BASF Corporation. No competing interests have been declared.

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Table 1. Sources of herbicides used for field and greenhouse experiments.

Common name	Trade name	Manufacturer	Manufacturer location	Manufacturer website
Glufosinate	Liberty®	BASF Corporation	Research Triangle Park, NC	www.basf.com
Glyphosate	Roundup Powermax®	Bayer CropScience, LLC	St. Louis, MO	www.bayer.com
Paraquat	Gramoxone®	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta.com
Saflufenacil	Sharpen®	BASF Corporation	Research Triangle Park, NC	www.basf.com
Trifludimoxazin	Tirexor®	BASF Corporation	Research Triangle Park, NC	www.basf.com

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Table 2. Relative potency, compared to trifludimoxazin, of herbicides applied to waterhemp and giant ragweed in greenhouse experiments, based on calculated GR_{50} values from preliminary dose response assays and analysis via four-parameter log-logistic regression.

	Herbicide			
Weed Species	Glufosinate	Glyphosate	Paraquat	Saflufenacil
Waterhemp	20:1	300:1	30:1	0.75:1
Giant ragweed	35:1	65:1	30:1	0.3:1

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Table 3. Calculated GR_{50} values from greenhouse experiments, as determined by non-linear regression using a log-logistic four-parameter model.

Herbicide	Waterhemp	Giant ragweed
	GR_{50} Value (± 95% CI)	
	g ai/ae ha^{-1}	
Trifludimoxazin	0.17 (0.12 to 0.21)	0.92 (0.63 to 1.21)
Glufosinate	43.6 (11.3 to 75.9)	49.2 (38.9 to 59.7)
Glyphosate	66.8 (41.4 to 92.2)	45.5 (33.4 to 57.6)
Paraquat	9.91 (8.49 to 11.3)	23.6 (16.8 to 30.4)
Saflufenacil	0.15 (0.13 to 0.17)	0.38 (0.21 to 0.44)
Trifludimoxazin + glufosinate	7.60 (6.20 to 9.00)	21.2 (9.30 to 33.2)
Trifludimoxazin + glyphosate	37.0 (27.8 to 46.2)	37.5 (18.9 to 56.2)
Trifludimoxazin + paraquat	4.27 (3.70 to 4.85)	17.9 (13.7 to 22.2)
Trifludimoxazin + saflufenacil	0.17 (0.15 to 0.18)	0.38 (0.27 to 0.48)

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Table 4. Average waterhemp control from field experiments conducted near Brookston, IN in 2017 and 2018[a].

Trifludimoxazin	Tank-mix herbicide[c]	Visual control estimate[b]				Biomass reduction
		3 DAA		28DAA		
		Marked plants	Whole plot	Marked plants	Whole plot	
g ai ha^{-1}		%				% of NTC
12.5	-	95a	83a	94a	87a	95a
25	-	96a	85a	99a	89a	95a
-	Glufosinate	32b	28b	36b	41b	58b
-	Glyphosate	5c	7b	12b	22b	23c
-	Paraquat	97a	95a	100a	93a	97a
-	Saflufenacil	89a	73a	81a	76a	89a
12.5	Glufosinate	90a	85a	91a	73a	92a
25	Glufosinate	94a	91a	99a	81a	94a
12.5	Glyphosate	91a	85a	92a	82a	89a
25	Glyphosate	96a	83a	97a	91a	96a
12.5	Paraquat	98a	95a	100a	86a	97a
25	Paraquat	97a	97a	100a	94a	97a
12.5	Saflufenacil	96a	85a	95a	76a	94a
25	Saflufenacil	97a	87a	98a	83a	97a
P-value		<0.001	<0.001	<0.001	<0.001	<0.001

[a]Abbreviations: DAA, days after application; NTC, non-treated check

[b]Means within a column followed by the same letter do not differ according to Tukey's Honestly Significant Difference (α = 0.05).

[c]Rates for tank-mix herbicides: glufosinate = 590 g ai ha^{-1}, glyphosate = 870 g ae ha^{-1}, saflufenacil = 25 g ai ha^{-1}, paraquat = 840 g ai ha^{-1}.

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Table 5. Tank-mix interactions, as determined by analysis via Colby’s method, for marked waterhemp plants in field experiments conducted near Brookston, IN in 2017 and 2018[a,b].

		Control 28 DAA				Biomass reduction			
Trifludimoxazin rate	Tank-mix herbicide	Obs.	Exp.	P-value	Int.	Obs.	Exp.	P-value	Int.
g ai/ae ha^{-1}	g ai/ae ha^{-1}	—— % ——				—— % ——			
12.5	12.5	94				95			
25	25.0	99				95			
-	-	36				58			
-	-	12				23			
-	Glufosinate	100				97			
-	Glyphosate	81				89			
12.5	Paraquat	91	95	0.5187	Add.	**92**	**98**	**0.0194**	**Ant.**
25	Saflufenacil	95	99	0.4780	Add.	94	98	0.7039	Add.
12.5	Glufosinate	92	95	0.5778	Add.	89	92	0.6027	Add.
25	Glufosinate	97	99	0.4177	Add.	96	92	0.3476	Add.
12.5	Glyphosate	100	100	0.9876	Add.	97	100	**<0.0001**	**Ant.**
25	Glyphosate	100	100	0.9264	Add.	**97**	**100**	**0.0010**	**Ant.**
12.5	Paraquat	95	99	0.1707	Add.	94	99	0.0554	Add.
25	Paraquat	98	99	0.2602	Add.	**97**	**99**	**0.0043**	**Ant.**

[a]Abbreviations: Add., additive; Ant., antagonism; DAA, days after application; Exp., expected value; Int., interaction; NTC, non-treated check; Obs., observed value.

[b]Bold text is used to indicate interactions that are not additive (i.e. antagonistic or synergistic).

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Table 6. Giant ragweed control from field experiments conducted at Lafayette, IN in 2017 and 2018[a].

		Visual control estimate[b]				
		3 DAA		21DAA		
Trifludimoxazin	Tank-mix herbicide[c]	Marked plants	Whole plot	Marked plants	Whole plot	Biomass reduction
g ai ha^{-1}		%				% of NTC
12.5	-	83a	80ab	78b	73b	68d
25	-	85a	83ab	79b	74b	74cd
-	Glufosinate	53b	54bc	100a	96a	85abc
-	Glyphosate	25c	25c	79b	67b	76bcd
-	Paraquat	96a	93a	100a	95a	94a
-	Saflufenacil	92a	87a	100a	98a	89ab
12.5	Glufosinate	78a	73ab	100a	95a	85abc
25	Glufosinate	80a	75ab	100a	95a	87abc
12.5	Glyphosate	82a	79ab	99a	91a	88ab
25	Glyphosate	88a	82ab	99a	95a	92a
12.5	Paraquat	96a	96a	100a	99a	93a
25	Paraquat	97a	95a	100a	98a	90ab
12.5	Saflufenacil	91a	87a	100a	98a	90ab
25	Saflufenacil	93a	87a	100a	98a	92a
P-value		<0.001	<0.001	<0.001	<0.001	<0.001

[a]Abbreviations: DAA, days after application; NTC, non-treated check

[b]Means within a column followed by the same letter do not differ according to Tukey's Honestly Significant Difference (α = 0.05).

[c]Rates for tank-mix herbicides: glufosinate = 590 g ai ha^{-1}, glyphosate = 870 g ae ha^{-1}, saflufenacil = 25 g ai ha^{-1}, paraquat = 840 g ai ha^{-1}.

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Table 7. Mixture interactions, as determined by analysis via Colby's method, for marked giant ragweed plants in field experiments conducted at Lafayette, IN in 2017 and 2018[a,b].

		Control 21 DAA				Biomass reduction			
Trifludimoxazin rate	Tank-mix herbicide	Obs.	Exp.	P-value	Int.	Obs.	Exp.	P-value	Int.
g ai/ae ha^{-1}	g ai/ae ha^{-1}	—— % ——				—— % ——			
12.5	12.5	78				68			
25	25.0	79				74			
-	-	100				85			
-	-	79				76			
-	Glufosinate	100				94			
-	Glyphosate	100				89			
12.5	Paraquat	100	100	0.9798	Add	85	93	0.1746	Add
25	Saflufenacil	100	100	0.9913	Add	87	95	0.1613	Add
12.5	Glufosinate	99	97	0.1028	Add	88	91	0.5658	Add
25	Glufosinate	**99**	**96**	**0.0237**	**Syn**	92	93	0.6819	Add
12.5	Glyphosate	100	100	0.9955	Add	93	97	0.0798	Add
25	Glyphosate	100	100	0.9801	Add	90	98	0.0923	Add
12.5	Paraquat	100	100	0.3506	Add	90	94	0.4206	Add
25	Paraquat	100	100	0.8516	Add	92	96	0.2024	Add

[a]Abbreviations: Add., additive; Ant., antagonism; DAA, days after application; Exp., expected value; Int., interaction; NTC, non-treated check; Obs., observed value.

[b]Bold text is used to indicate interactions that are not additive (i.e. antagonistic or synergistic).

Table 8. Horseweed control from field experiments conducted near Brookston, IN in 2017 and 2018[a].

Trifludimoxazin	Mixture herbicide[c]	Visual control estimate[b] 3 DAA Marked plants	3 DAA Whole plot	28DAA Marked plants	28DAA Whole plot	Biomass reduction
g ai ha^{-1}		%	%	%	%	% of NTC
12.5	-	12cd	13cd	9b	10b	15b
25	-	18cd	19cd	10b	13b	17b
-	Glufosinate	84ab	76b	100a	92a	90a
-	Glyphosate	7d	8d	17b	18b	25b
-	Paraquat	94a	91ab	94a	78a	87a
-	Saflufenacil	83ab	81ab	98a	92a	88a
12.5	Glufosinate	89ab	89ab	99a	91a	87a
25	Glufosinate	90ab	90ab	100a	91a	85a
12.5	Glyphosate	25c	26c	29b	23b	22b
25	Glyphosate	22cd	25c	17b	21b	33b
12.5	Paraquat	92ab	90ab	93a	81a	88a
25	Paraquat	95a	92a	91a	81a	88a
12.5	Saflufenacil	85ab	87ab	99a	83a	86a
25	Saflufenacil	77b	78ab	93a	93a	85a
P-value		<0.001	<0.001	<0.001	<0.001	<0.001

[a]Abbreviations: DAA, days after application; NTC, non-treated check

[b]Means within a column followed by the same letter do not differ according to Tukey's Honestly Significant Difference ($\alpha = 0.05$).

[c]Rates for mixture herbicides: glufosinate = 590 g ai ha^{-1}, glyphosate = 870 g ae ha^{-1}, saflufenacil = 25 g ai ha^{-1}, paraquat = 840 g ai ha^{-1}.

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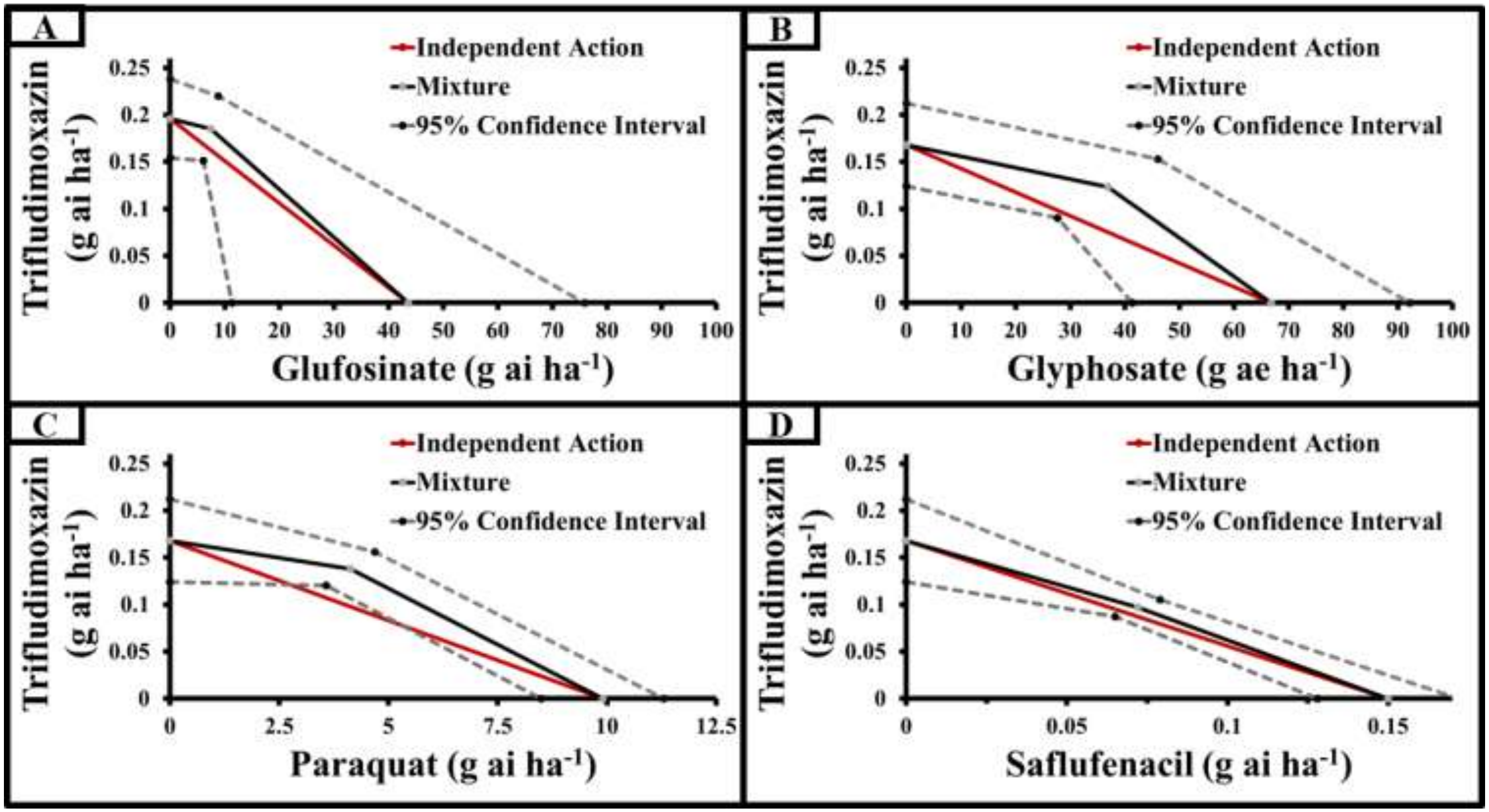

Figure 1: Isobole analysis for GR_{50} values utilizing combinations of trifludimoxazin and A) glufosinate, B) glyphosate, C) paraquat, or D) saflufenacil, applied to waterhemp. The independent action line, denoted in red, indicates combinations of each herbicide expected to elicit 50% control. Deviation of the GR_{50} value and corresponding 95% confidence interval from the independent action line indicates an antagonistic interaction for trifludimoxazin plus saflufenacil, whereas all other combinations are additive.

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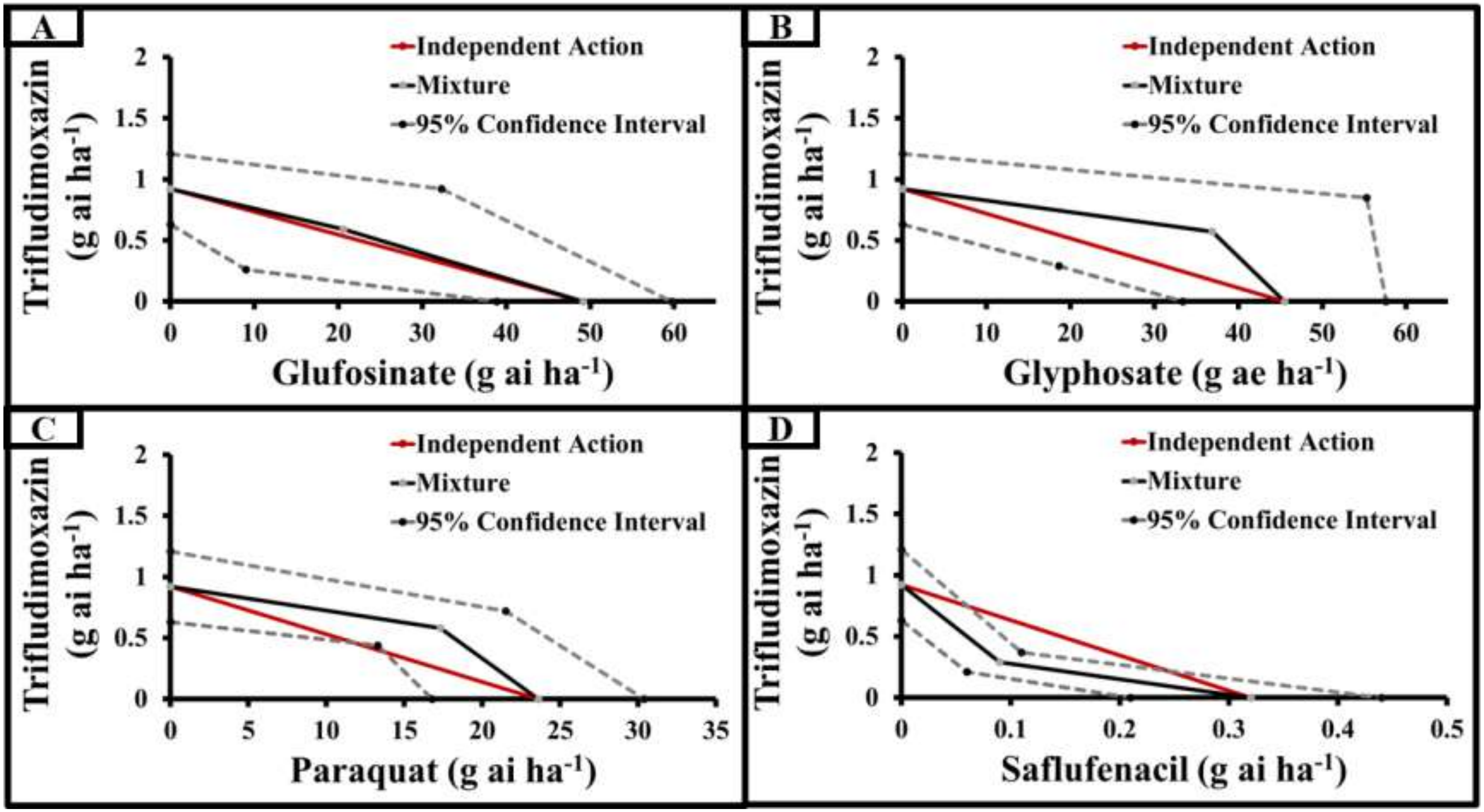

Figure 2: Isobole analysis for GR_{50} values utilizing combinations of trifludimoxazin and A) glufosinate, B) glyphosate, C) paraquat, or D) saflufenacil, applied to giant ragweed. Deviation of the GR_{50} value and corresponding 95% confidence interval from the independent action line indicates antagonism and synergism for combinations of trifludimoxazin plus paraquat, and trifludimoxazin plus saflufenacil, respectively. Combinations of trifludimoxazin with glufosinate or glyphosate are additive.

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