Avoiding Protoporphyrinogen Oxidase Inhibiting Herbicide Selection Pressure on Common Ragweed and Palmer amaranth in Soybean

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Academic Abstract

Palmer amaranth (*Amaranthus palmeri*) and common ragweed (*Ambrosia artemisiifolia*) can cause detrimental soybean yield loss. Due to widespread resistance to glyphosate and ALS-inhibiting herbicides, growers rely on protoporphyrinogen oxidase inhibiting herbicides (PPO) such as flumioxazin applied preemergence (PRE) and fomesafen postemergence (POST) to control both weeds. Experiments were conducted with the overarching goal of reducing PPO selection pressure for Palmer amaranth and common ragweed. Flumioxazin alone PRE controlled Palmer amaranth near 100%. However, sulfentrazone combined with pyroxasulfone or pendimethalin provided similar control to flumioxazin. Acetochlor and linuron controlled common ragweed ≤74%, yet controlled Palmer amaranth ≥96%. Glufosinate applied POST controlled Palmer amaranth and common ragweed 74-100%, regardless of PRE treatment. Flumioxazin PRE followed by fomesafen POST controlled common ragweed well; however, several non-PPO herbicide treatments or programs with only 1 PPO-inhibiting herbicide provided similar common ragweed control as the 2 PPO system (flumioxazin followed by fomesafen). Treatments consisting of a PRE and POST herbicide controlled Palmer amaranth at least 80% and common ragweed 95%. To reduce PPO selection pressure, soybean producers growing glufosinate-resistant soybean may use flumioxazin PRE followed by glufosinate POST whereas non-glufosinate-resistant soybean growers should reduce PPO herbicide use by using a non-PPO herbicide PRE. Alternatively, these producers can effectively reduce PPO selection pressure by implementing residual combinations of a PPO-inhibiting herbicide + non-PPO with spectrums of weed control that overlap at either Palmer amaranth or common ragweed.

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General Audience Abstract

Soybean producers planted 35.4 million hectares in the US during 2018. Palmer amaranth (*Amaranthus palmeri*) and common ragweed (*Ambrosia artemisiifolia*) are both common and problematic in soybean production. The introduction of a glyphosate-resistant soybean cultivars coupled with glyphosate allowed soybean producers to easily control these weeds along with many other broadleaf and grass weeds. However, over reliance on glyphosate selected for biotypes of common ragweed and Palmer amaranth resistant to the herbicide. In response, soybean producers have reverted to preemergence (PRE) herbicides and alternative modes of action postemergence (POST) to control these herbicide-resistant weeds. One such herbicide mode of action is inhibition of protoporphyrinogen oxidase (PPO). Flumioxazin and fomesafen are both PPO-inhibiting herbicides and have been widely used in soybean, however increasing reliance on PPOs has selected for resistant common ragweed and Palmer amaranth biotypes. This research focused on reducing risk of PPO-inhibiting herbicide resistance development ("selection pressure") by finding alternatives to or combinations with PPO-inhibiting herbicides that would effectively control both weeds and thus preserve effectiveness of a valuable herbicide group.

Of PRE herbicides applied alone, flumioxazin was the only treatment to control Palmer amaranth >79% 14 DA-PRE at Painter 2017. However, combination of PRE herbicides such as sulfentrazone or metribuzin in combination with pyroxasulfone, and pendimethalin + sulfentrazone, all controlled Palmer amaranth well. While metribuzin and pendimethalin alone did not provide as much control, a POST application of glufosinate coupled with these residual

herbicides adequately controlled Palmer amaranth. Soybean producers can effectively control Palmer amaranth with a non-PPO PRE herbicide followed by glufosinate postemergence (POST) or residual combinations of a PPO + non-PPO while reducing risk of herbicide resistance development.

Several PRE herbicide treatments adequately controlled common ragweed. During 2017, residual herbicides that controlled common ragweed at least 90% included flumioxazin, flumioxazin + clomazone, linuron, or metribuzin, fomesafen + linuron, and linuron + clomazone. All treatments controlled common ragweed greater than 94% during 2018, except metribuzin, linuron, and clomazone, which controlled the weed 75, 86, and 90%, respectively. Fomesafen alone or in combination with metribuzin controlled common ragweed 80 to 84%. Regardless of PRE, glufosinate POST controlled common ragweed 99% 56 and 70 days after planting (DAP). In fields infested with common ragweed yet to develop PPO resistance, growers should use a non-PPO herbicide in combination with flumioxazin PRE. Additionally, tank mixtures of effective MOAs PRE followed by glufosinate rather than a PPO POST may reduce herbicide selection pressure.

The final study set out to determine which was more critical to controlling herbicide-resistant Palmer amaranth and common ragweed in soybean, a PPO-inhibiting herbicide applied PRE or POST. Flumioxazin applied PRE controlled both weeds almost completely. Acetochlor and linuron did not control common ragweed as well, but controlled Palmer amaranth >96%. Both metribuzin and clomazone were weaker on common ragweed and Palmer amaranth. However, all PRE herbicide treatments followed by glufosinate or fomesafen controlled Palmer amaranth and common ragweed at least 80 and 95%, respectively. To reduce PPO selection pressure, soybean producers growing glufosinate-resistant soybean may use flumioxazin PRE followed by glufosinate POST whereas non-glufosinate-resistant growers should reduce PPO herbicide use by using a non-PPO herbicide PRE. Alternatively, these producers can effectively reduce PPO selection pressure by implementing residual combinations of a PPO-inhibiting herbicide + non-PPO with spectrums of weed control that overlap at either Palmer amaranth or common ragweed.

Results from these experiments suggest PPO-inhibiting herbicides are critical for common ragweed and Palmer amaranth control. Previous research has shown effective tank mixtures with various effective MOAs has reduced the risk of herbicide resistance development. Protoporphyrinogen oxidase herbicides should be used sparingly and in combination with effective non-PPO herbicides to reduce selection pressure.

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Abstract

Palmer amaranth is a problematic weed of all crops including soybeans due to its competiveness, adaptability, and prolific seed production. In response to glyphosate and ALS resistance development in Palmer amaranth, use of protoporphyrinogen oxidase inhibiting herbicides (PPO) to control Palmer amaranth increased and over reliance on this herbicide mode of action recently selected for PPO-resistant biotypes. The objective of this study was to find residual alternatives to PPO-inhibiting herbicides for preemergence (PRE) Palmer amaranth control. Flumioxazin applied PRE controlled Palmer amaranth more effectively than any other stand-alone residual herbicide. However, combination of pyroxasulfone + sulfentrazone or metribuzin, and sulfentrazone + pendimethalin provided similar Palmer amaranth control as flumioxazin. Metribuzin and pendimethalin alone or in combination with one another were least effective. Regardless of PRE herbicide treatment, glufosinate applied postemergence (POST) controlled Palmer amaranth well. Results of these experiments demonstrate soybean producers can effectively control Palmer amaranth with non-PPO PRE herbicides followed by glufosinate POST or residual combinations of a PPO + non-PPO while reducing PPO-selection pressure.

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Wats) is one of the most problematic weeds infesting soybean (Ward et al. 2013). Attributes contributing to its troublesomeness include high seed production, adaptability, and competitiveness (Ehleringer 1983; Monks and Oliver 1988; Place et al. 2008; Wright et al. 1999). Palmer amaranth is dioceus, having separate male and female plants (Bryson and DeFelice 2009). Pollen can travel long distances, mainly transported by wind (Ward et al. 2013). Pollen transfer of herbicide resistant traits has been previously discussed (Sosnoskie et al. 2009). The weed has the capability to produce one million seeds under good growing conditions and limited inter-and intraspecific competition (Sosnoskie et al. 2014). Under normal field conditions, one female is capable of producing several hundred thousand seeds (Keeley et al. 1987). Palmer amaranth has the ability to grow more than 2.54 cm per day and can grow to a height of over 2.0 m (Sauer 1955; Sosnoskie et al. 2014). A C_4 plant, Palmer amaranth is adaptable to hot and dry conditions (Ehleringer 1983). A quickly established soybean canopy, capturing 80 to 90% sunlight, is typically enough to reduce competition from many weeds (Noguchi 1992). However, Palmer amaranth had adapted morphologically and photosynthetically to continue growth when 13% or more light penetrates the soybean canopy (Jha et al. 2008; Monks and Oliver 1988).

The aforementioned characteristics allow Palmer amaranth to compete with many crops including soybean, corn, and cotton (Culpepper et al. 2010; Flessner et al. 2016; MacRae et al. 2008; Massigna et al. 2001; Morgan et al. 2001; Rowland et al. 1999; Webster 2009). Yield of corn and cotton grown in competition with eight Palmer amaranth plants m^{-1} row could be reduced up to 91 and 92%, respectively (MacRae et al. 2008; Massigna et al. 2001; Morgan et al.

2001; Rowland et al. 1999). Klingaman and Oliver (1994) reported 0.33 and 10 Palmer amaranth plants m^{-1} row decreased soybean yield 17 and 68%, respectively.

Introduction of glyphosate-resistant soybean in 1996 transformed weed control (Wilcut et al. 1995). Although glyphosate once provided excellent Palmer amaranth control, repeated and exclusive use of glyphosate selected for Palmer amaranth biotypes resistant to the herbicide (Bond et al. 2006; Corbett et al. 2004). Glyphosate-resistant (GR) Palmer amaranth was first confirmed in Georgia and North Carolina during 2005; in the U.S., there are now 28 states with confirmed GR Palmer amaranth biotypes (Culpepper et al. 2008; Heap 2018). Palmer amaranth now has confirmed resistance to six different sites of action including 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase, acetolactate synthase (ALS)-, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-, microtubule-, photosystem II-, and protoporphyrinogen (PPO)-inhibiting herbicides (Heap 2018). More alarming, biotypes of Palmer amaranth resistant to glyphosate and ALS-inhibiting herbicides are widespread and biotypes resistant to glyphosate, ALS-inhibiting herbicides, and PPO-inhibiting herbicides are now established in the Midsouth and Midwest U.S. (Heap 2018). To control multiple-resistant biotypes of Palmer amaranth, producers have returned to weed management tactics popular prior to the commercialization glyphosate-resistant crops including residual herbicide use (Norsworthy et al. 2012). Several studies have shown preemergence (PRE) herbicides to reduce weed densities allowing for greater flexibility in choice and timing of postemergence (POST) herbicides (Barnes and Oliver 2004; Ellis and Griffin 2002). Although a POST application was still necessary, Ellis and Griffin (2002) noted sulfentrazone and metribuzin in combination with chlorimuron delayed a POST application of glyphosate by 7 days. A study conducted by Barnes and Oliver (2004) found soybean yields were highest when a PRE followed by (fb) POST herbicide application was utilized in comparison to a single POST herbicide application alone; superior control in high densities of weeds was also noted with PRE fb POST.

Protoporphyrinogen-inhibiting herbicides have been sold since the 1960s for weed control in multiple crops, with resistance not developing until first confirmed in a biotype of common waterhemp (*Amaranthus tuberculatus*), a close relative of Palmer amaranth, from Kansas in 2001 (Bryson and DeFelice 2009; Heap 2018; Shoup et al. 2003). Where glyphosate- and ALS-resistant Palmer amaranth exists, PPO-inhibiting herbicides are frequently recommended by extension personnel (Curran et al. 2018; Everman 2018; Flessner and Cahoon 2018). Flumiclorac, flumioxazin, fomesafen, lactofen, acifluorfen, and sulfentrazone, all PPO-inhibiting herbicides, are popular herbicide choices where PPO-resistance has yet to develop (Curran et al. 2018; Everman 2018; Flessner and Cahoon 2018). In fact, a research firm reported flumioxazin was the most widely used PRE during 2009 (Valent 2010). Due to their effectiveness, it is also a common practice to use multiple PPO-inhibiting herbicides to control Palmer amaranth (Legleiter and Johnson 2013). Often, soil-applied PRE herbicides such as flumioxazin or sulfentrazone containing products are fb fomesafen or lactofen POST (Ward et al. 2013). Powell (2014) reported flumioxazin and flumioxazin + pyroxasulfone controlled Palmer amaranth 85% or greater whereas pyroxasulfone alone, *S*-metolachlor, metribuzin, and pendimethalin all provided less than 56% control. When sulfentrazone was applied at 0.28 kg ha^{-1}, it joined flumioxazin and flumioxazin + pyroxasulfone with the most Palmer amaranth control (Powell 2014). Additionally, Jordan et al. (2011) observed 70% Palmer amaranth control with sulfentrazone PRE. When flumioxazin in combination with pyroxasulfone or *S*-metolachlor was fb fomesafen applied to 7 cm Palmer amaranth, consistent and effective control was accomplished (Dillon et al. 2011). Norsworthy et al. (2008) found that fomesafen applied POST controlled 100% of glyphosate-susceptible and -resistant Palmer amaranth. Lactofen controlled Palmer amaranth at least 85%; additionally, lactofen provided near 100% control of several other *Amaranthus* species (Sweat et al. 1998). Continued, almost exclusive, reliance on PPO-inhibiting herbicides to control Palmer amaranth in soybean places immense selection pressure on PPO-resistant biotypes in areas yet to develop resistance (Reiofeli et al. 2016).

The objective of this study was to evaluate residual alternatives to PPO-inhibiting herbicides for Palmer amaranth control, with the overall goal of reducing PPO selection pressure in soybean production.

Materials and Methods

Experiments were conducted near Painter, Virginia at the Eastern Shore Agricultural and Research Extension Center (AREC) (37.59186°, -75.82224°) and Suffolk, Virginia at the Tidewater AREC (36.68315°, -76.75790°) during 2017 and two separate fields (37.59163°, -75.82308° and 37.59075°, -75.82345°) at Painter during 2018. Soils included a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult) near Painter with 1% organic matter (OM) and pH 6.4 and a Suffolk loamy sand (fine-loamy, siliceous, semiactive, thermic Typic Hapludult) with 0.9% OM and pH 6.3 near Suffolk. An endemic population of Palmer amaranth was present in fields at Painter at a density of 2 plants m^{-2}, whereas glyphosate-susceptible Palmer amaranth was sown at Suffolk to achieve a final plant density of 17 plants m^{-2}.

Soybean was planted into conventionally prepared land (plowed and cultivated) at Painter and following strip-tillage at Suffolk. Seeding rate at Painter was 371,000 seeds ha^{-1} and 413,000 seeds ha^{-1} at Suffolk. Glufosinate-resistant soybean cultivar 'DYNA GRO S49LL34' was planted at Painter on May 19, 2017. A glyphosate- and dicamba-resistant cultivar 'AG

48X7 RR2XF' was planted on May 17, 2017 at Suffolk. Glufosinate-resistant soybean cultivar 'CZ 4818LL' (Bayer CropScience, Research Triangle Park, NC) was planted at both fields near Painter in 2018 on May 9, 2018 and June 6, 2018, respectively. Soybean planting dates listed in Table 1. Experimental design was a randomized complete block with four replications at both locations. Plot size included four rows by 6 m long on 76 cm spaced rows at Painter and four rows by 9 m long on 91 cm spaced rows at Suffolk.

Preemergence herbicide treatments were applied immediately following planting. Herbicide application rates and sources are listed in Table 2. A nontreated check was included for comparison purposes. All plots, except nontreated checks, received glufosinate POST at Painter and glyphosate POST at Suffolk approximately 30 days after planting (DAP). Herbicide applications in Painter were made using a tractor mounted sprayer with XR8003 (TeeJet Technologies, Wheaton, IL) flat fan tractor nozzles, delivering 221 L ha^{-1} at 207 kPa. At Suffolk, all herbicide applications were made using a CO_2-pressurized backpack sprayer however, PRE herbicides were applied using AIXR11002 (TeeJet Technologies, Wheaton, IL) flat fan nozzles delivering 140 L ha^{-1} at 172 kPa whereas POST herbicides were applied using TTI110015 (TeeJet Technologies, Wheaton, IL) flat fan nozzles, delivering 140 L ha^{-1} at 234 kPA.

Visible estimates of Palmer amaranth control and soybean injury were collected according to (Frans et al. 1986) at 14, 28, 42, 56, and 70 DAP. Palmer amaranth densities were determined by counting the number of plants in a m^{-2} 7 days prior to and after POST applications were made. The center two rows of plots were harvested during mid-November in 2017 and mid-October in 2018, using a small plot combine to determine soybean yield.

Data for soybean injury, Palmer amaranth control, Palmer amaranth density, soybean injury, and soybean yield were subjected to analysis of variance using JMP PRO 13 (SAS Institute Inc., Cary, NC). Means were separated using Fishers Protected LSD at an alpha level of ≤ 0.05. Herbicide treatments was treated as a fixed factor whereas location and replication were treated as random.

Results and Discussion

Soybean response. In general, flumioxazin and residual herbicide treatments containing flumioxazin were most injurious (necrosis and growth reduction), especially 14 DA-PRE (Table 3) when 26 to 31% visible injury was observed. Flumioxazin, flumioxazin + metribuzin, flumioxazin + pyroxasulfone, and flumioxazin + pendimethalin injured soybean 26, 28, 31, and 26%, respectively. Sulfentrazone containing treatments were less injurious than flumioxazin 14 DA-PRE but remained moderately injurious (9 to 15%). Soybean injury 14 DA-PRE from all non-PPO herbicide treatments ranged 1 to 6% and was generally less than injury from flumioxazin and sulfentrazone containing treatments. Despite early season injury, soybean quickly recovered. Soybean injury was much less 28 and 42 DA-PRE, when ≤11% and ≤4% injury was observed, respectively, and few differences were noted among treatments.

Flumioxazin and sulfentrazone have been noted to injure soybean, especially if heavy rainfall is observed immediately after planting (Hartzler 2017; Mahoney et al. 2014; Swantek et al. 1998). It should also be pointed out that flumioxazin and sulfentrazone rates used in these experiments were maximum permitted for coarse-textured soils (Anonymous 2010; Anonymous 2011). High rates of these herbicides were used with the goal of achieve prolonged residual

Palmer amaranth control; soybean producers would likely use lesser rates to avoid injury. High rates of these herbicides coupled with coarse soil texture and rain immediately after planting may explain increased soybean injury observed early in the season. However, like previous research, early season soybean injury was transitory with little injury observed 42 DA-PRE (Mahoney et al. 2014; McNaughton et al. 2014).

Palmer Amaranth Control. The two-way interaction of herbicide treatment by environment was significant for Palmer amaranth control 14 and 28 DA-PRE; hence, data for Palmer amaranth control at these rating intervals are presented by location.

Flumioxazin (100%) and residual combinations including flumioxazin (100%) provided excellent Palmer amaranth control 14 DA-PRE across all locations whereas other residual treatments were less consistent Table 4. At the two locations with densest Palmer amaranth, Painter 2017 and Suffolk 2017, sulfentrazone alone, metribuzin alone, and pendimethalin alone were less effective than flumioxazin alone 14 DA-PRE. Conversely, sulfentrazone combinations metribuzin combinations, and pyroxasulfone + pendimethalin and were similarly effective as flumioxazin 14 DA-PRE at Painter 2017. At Suffolk 2017, pyroxasulfone as well as sulfentrazone + pyroxasulfone or pendimethalin, metribuzin + pyroxasulfone, and pyroxasulfone + pendimethalin controlled Palmer amaranth similar to flumioxazin 14 DA-PRE. At both Painter fields during 2018, all residual herbicide treatments controlled Palmer amaranth 98 to 100% and no difference among treatments were noted.

At 28 DA-PRE, residual combinations containing flumioxazin continued to control Palmer amaranth well (99 to 100%), regardless of location (Table 5). Comparable to Palmer amaranth control 14 DA-PRE, sulfentrazone combinations controlled Palmer amaranth similar to flumioxazin treatments 28 DA-PRE across all locations. Moreover, all sulfentrazone combinations controlled Palmer amaranth 99 to 100% at this time, except sulfentrazone alone and sulfentrazone + metribuzin at Suffolk 2017. At 28 DA-PRE, metribuzin alone and pendimethalin alone were the least consistent residual treatments for Palmer amaranth control. Metribuzin alone controlled Palmer amaranth 74, 36, 86, and 95% at Painter 2017, Suffolk 2017, Painter Field 1 2018, and Painter Field 2 2018, respectively. Likewise, pendimethalin controlled the weed 48 to 95% across locations. The metribuzin rate used in these experiments was 280 g ai ha^{-1} and was chosen based on the coarse-textured soils present at each location. Metribuzin is capable of injuring soybean on coarse-textured soils with low organic matter (Street et al. 1987). The relatively low rate of metribuzin used for this study may explain why Palmer amaranth control by metribuzin was poor. Palmer amaranth control by pendimethalin is well documented to be inconsistent, especially where the herbicide is not incorporated with tillage (Whitaker et al. 2011). In a study conducted in Georgia and North Carolina, Palmer amaranth control with pendimethalin ranged 44 to 82% and 0 to 64% 20 and 40 days after application, respectively (Whitaker et al. 2011). Relying solely on metribuzin or pendimethalin applied alone for Palmer amaranth control would be unwise. Activity of these herbicides was greatly improved with the addition of a tank-mix partner like flumioxazin, sulfentrazone, or pyroxasulfone; therefore, in fields infested with Palmer amaranth, if a soybean producer uses metribuzin or pendimethalin, it would be prudent to tank-mix one of the aforementioned tank-mix partners. It is also worthy to note that pyroxasulfone alone, metribuzin + pyroxasulfone, and pyroxasulfone + pendimethalin, all residual herbicide treatments that did not include a PPO-inhibiting herbicide, controlled Palmer amaranth similar to treatments containing flumioxazin or sulfentrazone 28 DA-PRE. Protoporphyrinogen oxidase-inhibiting herbicides are heavily relied upon for residual and postemergence Palmer amaranth control in soybean (Salas et al. 2016). Because of intense selection pressure, Palmer amaranth biotypes resistant to PPO-inhibiting herbicides have developed in the mid-South and Midwest US (Heap 2018; Salas et al. 2016). Pyroxasulfone and pyroxasulfone combinations evaluated in these experiments seemed to be viable candidates for reducing PPO-selection pressure in regions yet to develop resistance and for residual control of PPO-resistant Palmer amaranth biotypes where they currently exist.

Glufosinate, if applied timely (≤ 10 cm Palmer amaranth), controls Palmer amaranth well (Corbett et al. 2004). Likewise, in these experiments, following glufosinate applied POST, Palmer amaranth control was excellent and few differences were observed (Table 6). Following PRE herbicides applied at soybean planting and glufosinate applied POST, Palmer amaranth was controlled 93 to 100%, 93 to 100%, and 97 to 100% 14, 28, and 42 DA-POST, respectively. In wide-row soybean, flumioxazin, pendimethalin, or sulfentrazone PRE and glufosinate POST provided better weed control than that of no PRE and glufosinate POST (Beyers et al. 2002). Sulfentrazone or flumioxazin fb glufosinate controlled 90 to 95% of common waterhemp (*Amaranthus rudis* Sauer) and pendimethalin fb glufosinate 86 to 91% (Beyers et al 2002).

In general, data for Palmer amaranth density followed a similar trend as visible control data. Palmer amaranth density in nontreated checks, prior to glufosinate POST, averaged 4, 17, 1, and 2 plants m^{-2} at Painter 2017, Suffolk 2017, Painter Field 1 2018, and Painter Field 2 2018, respectively (Table 7). All residual herbicide treatments at Painter 2017, Painter Field 1 2018, and Painter Field 2 2018 reduced Palmer amaranth density 75 to 100% compared to nontreated checks. Not all residual herbicide treatments at Suffolk 2017 reduced Palmer amaranth density relative to nontreated plots. At this location, all treatments except metribuzin alone, metribuzin + pendimethalin, and pendimethalin alone, reduced Palmer amaranth density 88 to 100% compared to the nontreated. Pendimethalin alone did not reduce Palmer amaranth density whereas metribuzin alone and metribuzin + pendimethalin were marginally effective, reducing density of the weed 59 to 71% relative to the nontreated. Following glufosinate, Palmer amaranth density was greatly reduced (Table 8). Palmer amaranth density at all Painter environments was 0 in treated plots. Additionally, at Suffolk Palmer amaranth density was zero 7 DA-POST, except metribuzin, metribuzin + pyroxasulfone or pendimethalin, pyroxasulfone, and pendimethalin.

Annual grass control. Predominated grasses evaluated included Texas millet (*Urochloa texana* Buckl.), large crabgrass (*Digitaria* sanguinalis (L.) Scop.), and foxtail species (*Setaria* spp.) and were rated together for a single annual grass control evaluation. Annual grass control data was separated by environment at 14 and 28 DA-PRE and pooled 14, 28, and 42 DA-POST. Residual herbicide treatments including flumioxazin evaluated in these experiments controlled annual grasses ≥ 96% (Table 9). Previous research reports mixed results concerning annual grass activity by flumioxazin (Grichar and Colburn 1996; Taylor-Lovell et al. 2002; Wilson et al. 2002). Flumioxazin controlled 78% of giant foxtail (*Setaria faberi* Herm.) when applied alone and 85% when combined with pendimethalin (Taylor-Lovell et al. 2002). A study also conducted on a loamy sand, flumioxazin only controlled 56 to 63% barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) (Wilson et al. 2002). In the current study, prior to glufosinate applied POST, these treatments provided 91 to 100% and 79 to 100% annual grass control 14 and 28 DA-PRE across locations, respectively. Annual grass control by pyroxasulfone was also ≥89%, except by pyroxasulfone alone at Suffolk 2017 (47%). Similarly, residual treatments including pendimethalin controlled annual grasses well, controlling the weeds 73 to 100% and 59 to 100% across locations 14 and 28 DA-PRE, respectively (Table 9 and 10). Effectiveness of pyroxasulfone and pendimethalin for annual grass control has been well documented (Walsh et al. 2010; Nakatani et al. 2016; Prostko et al. 2001; Yamaji et al. 2014). In a study analyzing the efficacy of pyroxasulfone, Yamaji and others (2014) observed 90% control of seven grass weeds including foxtails species with pyroxasulfone at 16 g ai ha^{-1}. Prostko et al. (2001) found pendimethalin applied PRE controlled grasses as well as when preplant incorporated (PPI).

Annual grass control by sulfentrazone and metribuzin alone was poor and are consistent with previous research (Bailey et al. 2002; Dirks et al. 2000; Westberg et al. 1989). At Painter 2017 and Suffolk 2017, where annual grass pressure was greatest, these herbicides controlled annual grasses no better than 74% 14 DA-PRE and 76% at 28 DA-PRE. Glufosinate controlled grasses $\geq$ 92% 14 DA-POST regardless of PRE herbicide treatment (Table 11).

Soybean Yield. Soybean yield in nontreated plots averaged 869 kg ha^{-1} (Table 12). All herbicide treatments improved soybean yield. Legleiter et al. (2009) found an increase in soybean yield with PRE fb POST controlling waterhemp. In this study, no differences in soybean yield were noted among treated plots. Soybean yield in plots treated with a PRE herbicide fb glufosinate or glyphosate POST ranged 3416 to 3811 kg ha^{-1}. Legleiter and others (2009) attested a yield increase to the efficacy of PPO-inhibiting herbicides, delaying early season weed emergence.

PPO-inhibiting herbicides, flumioxazin and sulfentrazone controlled Palmer amaranth well prior to glufosinate applied POST. At the same time, metribuzin and pendimethalin were less effective whereas pyroxasulfone alone controlled Palmer amaranth similarly to the PPO-inhibiting herbicides. Likewise, residual herbicide combinations that included one PPO-inhibiting herbicide (flumioxazin or sulfentrazone) were as effective as flumioxazin alone, sulfentrazone alone, and pyroxasulfone alone. Furthermore, except for metribuzin + pendimethalin at Suffolk 2017, residual combinations that did not include a PPO-inhibiting herbicide controlled Palmer amaranth similarly to flumioxazin, sulfentrazone, and PPO tank-mixes. Herbicide combinations are useful in avoiding herbicide resistance (Norsworthy et al. 2012). Biotypes of Palmer amaranth resistant to PPO-inhibiting herbicides are currently found in several mid-South and Midwest U.S. states (Heap 2018). In addition, over reliance on PPO-inhibiting herbicides for control of glyphosate- and ALS-resistant Palmer amaranth in regions yet to develop PPO resistance is likely to select PPO-resistant Palmer amaranth biotypes (Reiofeli et al. 2016). Results for these experiments suggest soybean producers concerned with selecting for PPO-resistance can effectively control Palmer amaranth by using residual combinations of non-PPO-inhibiting herbicides at soybean planting. Utilizing tank-mixes of effective MOA may reduce the risk of herbicide resistance (Norsworthy et al. 2012). Instead of abandoning the PPO-inhibiting herbicides, producers can use a non-PPO herbicide that effectively controls Palmer amaranth in combination with flumioxazin or sulfentrazone and accomplish the same feat of delaying PPO resistance.

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Tables

Table 1. Planting and herbicide application dates.

Location	Year	Planting Date	Herbicide application date	
			PRE	POST
Painter	2017	May 19	May 19	June 22
Suffolk	2017	May 17	May 17	June 14
Painter Field 1	2018	May 9	May 9	June 14
Painter Field 2	2018	June 6	June 6	July 9

Table 2. Herbicides used in experiments.[a]

Treatment	Trade Names	Application Rate ha^{-1}	Formula Concentration	Manufacturer
flumioxazin	Valor ® SX	107 g ai	51%	Valent U.S.A. Corp.
sulfentrazone	Spartan®	210 g ai	379 g ai L^{-1}	FMC Corporation
metribuzin	TriCor®	280 g ai	75%	United Phosphorous, Inc.
pyroxasulfone	Zidua®	119 g ai	85%	BASF Corporation
pendimethalin	Prowl® H_2O	799 g ai	456 g ai L^{-1}	BASF Corporation
flumioxazin + pyroxasulfone	Fierce®	88 + 112 g ai	76%	Valent U.S.A. Corp.
sulfentrazone + metribuzin	Authority MTZ® DF	176 + 265 g ai	45%	FMC Corporation
glyphosate[b]	Roundup PowerMAX®	1,262 g ae	535 g ae L^{-1}	Monsanto Company
glufosinate[c]	Liberty ® 280	656 g ai	280 g ai L^{-1}	Bayer CropScience

[a] Product labels, mailing addresses, and web site addresses can be found at www.cdms.net.

[b] Glyphosate applied at Suffolk 2017.

[c] Glufosinate applied at Painter 2017 and Painter Field 1 and 2 2018.

Table 3. Soybean response 14, 28, and 42 days after (DA) preemergence (PRE) herbicide treatments applied at planting in Virginia.[a]

Treatment [c]	Total injury (%)		
	14 DA-PRE	28 DA-PRE	42 DA-PRE
flumioxazin	26 b	4 cde	2 bcd
flumioxazin + metribuzin	28 ab	8 ab	0 de
flumioxazin + pyroxasulfone	31 a	11 a	4 a
flumioxazin + pendimethalin	26 b	4 b-e	0 de
sulfentrazone	13 c	6 bcd	1 cde
sulfentrazone + metribuzin	14 c	7 abc	2 bc
sulfentrazone + pyroxasulfone	9 d	3 de	2 bcd
sulfentrazone + pendimethalin	15 c	4 b-e	0 de
metribuzin	1 g	3 cde	0 de
metribuzin + pyroxasulfone	6 def	3 de	4 a
metribuzin + pendimethalin	5 ef	1 e	0 e
pyroxasulfone	3 fg	3 de	2 b-e
pendimethalin	4 efg	1 e	0 e
pyroxasulfone + pendimethalin	8 de	3 de	3 ab

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018)

[c] Herbicide use rates listed in Table 2.

Table 4. Palmer amaranth control 14 days after (DA) preemergence (PRE) herbicides applied at soybean planting. [a]

Treatment	Palmer amaranth control 14 DA-PRE (%)			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	100 a	100 a	100 a	100 a
flumioxazin + metribuzin	100 a	100 a	100 a	100 a
flumioxazin + pyroxasulfone	100 a	100 a	100 a	100 a
flumioxazin + pendimethalin	100 a	100 a	100 a	100 a
sulfentrazone	79 bcd	80 bcd	99 a	100 a
sulfentrazone + metribuzin	90 abc	73 cde	100 a	100 a
sulfentrazone + pyroxasulfone	96 a	99 a	100 a	100 a
sulfentrazone + pendimethalin	97 a	95 a	100 a	100 a
metribuzin	50 e	60 e	100 a	100 a
metribuzin + pyroxasulfone	93 ab	88 a	100 a	100 a
metribuzin + pendimethalin	92 ab	70 de	100 a	100 a
pyroxasulfone	75 cd	86 abc	100 a	100 a
pendimethalin	73 d	68 de	98 a	100 a
pyroxasulfone + pendimethalin	98 a	99 a	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates listed in Table 2.

Table 5. Palmer amaranth control 28 days after (DA) preemergence (PRE) herbicides applied at soybean planting. [a]

PRE [b]	Palmer amaranth control (%)			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	100 a	99 a	100 a	100 a
flumioxazin + metribuzin	100 a	100 a	100 a	100 a
flumioxazin + pyroxasulfone	100 a	100 a	100 a	100 a
flumioxazin + pendimethalin	100 a	99 a	100 a	100 a
sulfentrazone	100 a	83 ab	100 a	100 a
sulfentrazone + metribuzin	100 a	84 ab	100 a	100 a
sulfentrazone + pyroxasulfone	100 a	99 a	100 a	99 a
sulfentrazone + pendimethalin	100 a	94 a	100 a	100 a
metribuzin	74 b	36 c	86 b	95 b
metribuzin + pyroxasulfone	93 a	98 a	100 a	100 a
metribuzin + pendimethalin	93 a	73 b	94 ab	99 a
pyroxasulfone	100 a	98 a	100 a	100 a
pendimethalin	78 b	48 c	68 c	95 b
pyroxasulfone + pendimethalin	100 a	97 a	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Herbicide use rates listed in Table 2.

Table 6. Palmer amaranth control by preemergence (PRE) herbicides followed by glufosinate applied postemergence (POST), 14, 28, and 42 days after (DA) POST in Virginia. [a,b]

PRE [c]	POST [c.d]	Palmer amaranth control (%)		
		14 DA-POST	28 DA-POST	42 DA-POST
flumioxazin	glufosinate	100 a	100 a	100 a
flumioxazin + metribuzin	glufosinate	100 a	100 a	100 a
flumioxazin + pyroxasulfone	glufosinate	100 a	99 ab	100 a
flumioxazin + pendimethalin	glufosinate	100 a	100 a	100 a
sulfentrazone	glufosinate	99 ab	99 ab	100 a
sulfentrazone + metribuzin	glufosinate	100 a	100 a	100 a
sulfentrazone + pyroxasulfone	glufosinate	100 a	99 ab	100 a
sulfentrazone + pendimethalin	glufosinate	99 ab	99 ab	100 a
metribuzin	glufosinate	97 b	95 cd	97 c
metribuzin + pyroxasulfone	glufosinate	100 a	96 bcd	99 abc
metribuzin + pendimethalin	glufosinate	98 ab	98 abc	99 abc
pyroxasulfone	glufosinate	99 ab	98 abc	98 bc
pendimethalin	glufosinate	93 c	93 d	97 c
pyroxasulfone + pendimethalin	glufosinate	100 a	99 ab	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.
[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018)
[c] Herbicide use rates listed in Table 2.
[d] Postemergence applications made to 5-trifoliate soybean and 24 cm tall Palmer amaranth.

Table 7. Palmer amaranth densities prior to glufosinate applied postemergence in response to preemergence (PRE) herbicides.[a]

PRE [b]	Palmer amaranth density (plants m^{-2})			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	0 b	0 d	0 b	0 b
flumioxazin + metribuzin	0 b	0 d	0 b	0 b
flumioxazin + pyroxasulfone	0 b	0 d	0 b	0 b
flumioxazin + pendimethalin	0 b	0 d	0 b	0 b
sulfentrazone	0 b	2 cd	0 b	0 b
sulfentrazone + metribuzin	0 b	2 cd	0 b	0 b
sulfentrazone + pyroxasulfone	0 b	0 d	0 b	0 b
sulfentrazone + pendimethalin	0 b	1 d	0 b	0 b
metribuzin	1 b	7 bc	0 b	0 b
metribuzin + pyroxasulfone	0 b	0 d	0 b	0 b
metribuzin + pendimethalin	0 b	5 cd	0 b	0 b
pyroxasulfone	0 b	1 d	0 b	0 b
pendimethalin	1 b	11 ab	0 b	0 b
pyroxasulfone + pendimethalin	0 b	0 d	0 b	0 b
nontreated	4 a	17 a	1 a	2 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates listed in Table 2.

Table 8. Palmer amaranth densities in response to preemergence (PRE) herbicides followed by glufosinate and glyphosate applied postemergence.[a]

PRE [b]	POST [b,c,d]	Palmer amaranth density (plants m^{-2})			
		Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	glufosinate	0 b	0 d	0 b	0 b
flumioxazin + metribuzin	glufosinate	0 b	0 d	0 b	0 b
flumioxazin + pyroxasulfone	glufosinate	0 b	0 d	0 b	0 b
flumioxazin + pendimethalin	glufosinate	0 b	0 d	0 b	0 b
sulfentrazone	glufosinate	0 b	0 cd	0 b	0 b
sulfentrazone + metribuzin	glufosinate	0 b	0 d	0 b	0 b
sulfentrazone + pyroxasulfone	glufosinate	0 b	0 cd	0 b	0 b
sulfentrazone + pendimethalin	glufosinate	0 b	0 d	0 b	0 b
metribuzin	glufosinate	0 b	2 bc	0 b	0 b
metribuzin + pyroxasulfone	glufosinate	0 b	2 bc	0 b	0 b
metribuzin + pendimethalin	glufosinate	0 b	1 bcd	0 b	0 b
pyroxasulfone	glufosinate	0 b	1 bcd	0 b	0 b
pendimethalin	glufosinate	0 b	3 b	0 b	0 b
pyroxasulfone + pendimethalin	glufosinate	0 b	0 d	0 b	0 b
nontreated		1 a	17 a	1 a	2 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Herbicide use rates listed in Table 2.

[c] Postemergence applications made to 5-trifoliate soybean and 24 cm tall Palmer amaranth.

[d] Glufosinate applied at Painter 2017 and Painter Field 1 and 2 2018; glyphosate applied at Suffolk 2017.

Table 9. Annual grass control 14 days after (DA) preemergence (PRE) herbicides applied at soybean planting.[a]

PRE [b]	Annual grass control (%)[c]			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	100 a	99 a	98 abc	91 bc
flumioxazin + metribuzin	100 a	96 a	97 abc	98 ab
flumioxazin + pyroxasulfone	100 a	98 a	100 a	99 a
flumioxazin + pendimethalin	100 a	98 a	99 ab	97 ab
sulfentrazone	74 c	68 bc	89 c	93 abc
sulfentrazone + metribuzin	79 bc	79 ab	90 bc	99 ab
sulfentrazone + pyroxasulfone	98 a	81 ab	99 ab	99 ab
sulfentrazone + pendimethalin	96 a	85 ab	99 ab	85 cd
metribuzin	49 d	49 c	58 d	80 de
metribuzin + pyroxasulfone	97 a	85 ab	96 abc	99 a
metribuzin + pendimethalin	96 a	85 ab	93 abc	95 ab
pyroxasulfone	93 ab	47 c	89 c	98 ab
pendimethalin	91 ab	83	94 abc	73 e
pyroxasulfone + pendimethalin	98 a	81 ab	96 abc	99 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates listed in Table 2.

[c] Annual grasses consisted of Texas millet, large crabgrass, and foxtail species.

Table 10. Annual grass control 28 days after (DA) preemergence (PRE) herbicide applied at soybean planting.[a]

PRE [b]	Annual grass control (%)[c]			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	100 a	97 a	93 abc	79 de
flumioxazin + metribuzin	100 a	90 a	99 ab	92 ab
flumioxazin + pyroxasulfone	100 a	95 a	99 ab	97 a
flumioxazin + pendimethalin	100 a	96 a	98 abc	90 abc
sulfentrazone	69 b	45 cd	85 cd	75 de
sulfentrazone + metribuzin	76 b	64 a-d	86 bcd	84 bcd
sulfentrazone + pyroxasulfone	100 a	84 ab	100 a	92 ab
sulfentrazone + pendimethalin	98 a	81 ab	98 abc	73 e
metribuzin	23 c	39 d	51 e	60 f
metribuzin + pyroxasulfone	100 a	88 a	97 abc	96 a
metribuzin + pendimethalin	100 a	72 a-d	90 a-d	83 cd
pyroxasulfone	100 a	50 bcd	85 cd	96 a
pendimethalin	98 a	75 abc	77 d	59 f
pyroxasulfone + pendimethalin	100 a	86 a	99 ab	93 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates listed in Table 2.

[c] Annual grasses consisted of Texas millet, large crabgrass, and foxtail species.

Table 11. Annual grass control by preemergence (PRE) herbicides followed by glufosinate applied postemergence (POST), 14, 28, and 42 days after (DA) POST in Virginia. [a,b]

PRE [c]	POST [c,d]	Annual grass control (%)[e]		
		14 DA- POST	28 DA- POST	42 DA-POST
flumioxazin	glufosinate	100 a	99 abc	100 a
flumioxazin + metribuzin	glufosinate	100 a	99 ab	100 a
flumioxazin + pyroxasulfone	glufosinate	100 a	99 abc	99 a
flumioxazin + pendimethalin	glufosinate	100 a	100 a	100 a
sulfentrazone	glufosinate	98 ab	99 abc	99 abc
sulfentrazone + metribuzin	glufosinate	99 ab	99 abc	98 abc
sulfentrazone + pyroxasulfone	glufosinate	100 a	98 abc	99 abc
sulfentrazone + pendimethalin	glufosinate	100 a	99 abc	100 a
metribuzin	glufosinate	92 c	98 abc	98 abc
metribuzin + pyroxasulfone	glufosinate	100 a	98 abc	99 ab
metribuzin + pendimethalin	glufosinate	98 ab	99 abc	100 a
pyroxasulfone	glufosinate	100 a	97 bc	98 bc
pendimethalin	glufosinate	97 b	97 c	100 a
pyroxasulfone + pendimethalin	glufosinate	100 a	99 abc	98 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018)

[c] Herbicide use rates listed in Table 2.

[d] Postemergence applications made to 5-trifoliate soybean and 24 cm tall Palmer amaranth.

[e] Annual grasses consisted of Texas millet, large crabgrass, and foxtail species.

Table 12. Soybean yield in response to preemergence (PRE) herbicides followed by glufosinate and glyphosate applied postemergence in Virginia.[a,b]

PRE[c]	Soybean Yield (kg ha^{-1})
flumioxazin	3672 a
flumioxazin + metribuzin	3811 a
flumioxazin + pyroxasulfone	3605 a
flumioxazin + pendimethalin	3725 a
sulfentrazone	3763 a
sulfentrazone + metribuzin	3572 a
sulfentrazone + pyroxasulfone	3608 a
sulfentrazone + pendimethalin	3632 a
metribuzin	3735 a
metribuzin + pyroxasulfone	3719 a
metribuzin + pendimethalin	3597 a
pyroxasulfone	3735 a
pendimethalin	3416 a
pyroxasulfone + pendimethalin	3653 a
nontreated	869 b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates listed in Table 2.

Alternatives to Protoporphyrinogen Oxidase Inhibiting Herbicides (PPOs) for Residual Control of Common Ragweed (*Ambrosia artemisiifolia*) in Soybean

Abstract

Common ragweed is a common weed to soybean. Continued reliance on glyphosate and acetolactate synthase (ALS)-inhibiting herbicides for control selected for common ragweed biotypes resistant to these herbicides, and forced soybean producers to lean on Protoporphyrinogen oxidase (PPO)-inhibiting herbicides. Likewise, over reliance on PPOs has selected resistant biotypes. The objective of this study was to find residual alternatives to PPO-inhibitors for residual common ragweed control and concurrently reduce PPO-selection pressure. In 2017, flumioxazin, flumioxazin + clomazone, linuron, or metribuzin, fomesafen + linuron, and linuron + clomazone controlled common ragweed >89% whereas fomesafen applied alone or in combination with metribuzin or clomazone controlled common ragweed 80 to 84%. All treatments, except metribuzin and linuron, controlled common ragweed at least 90% during 2018. Although early season control varied among treatments, when PRE herbicides were followed by glufosinate postemergence (POST), common ragweed was controlled 99%, regardless of PRE. In fields infested with common ragweed yet to develop PPO resistance, growers should use a non-PPO herbicide in combination with flumioxazin PRE to reduce PPO-selection pressure.

Introduction

Common ragweed (*Ambrosia artemisiifolia* L.) is a problematic weed infesting soybean and other crops (Webster 2001). Mature plants can reach a height of 2 m and have a shallow taproot (Bryson and DeFelice 2009; Uva et al. 1997). Common ragweed is one of the earliest germinating summer annual broadleaf weeds (Stoller and Wax 1973; Myers et al. 2004; Werle et al. 2014). Myers et al. (2004) found that common ragweed had 10% germination by 150 soil degree days. Common ragweed is monoecious, having male and female flowers on different parts of the same plant (Uva et al. 1997). Mature plants have the capacity to produce 32,000 to 62,000 seeds (Davis et al. 2014).

Left uncontrolled, common ragweed is capable of reducing crop yields (Weaver 2001; Clay et al. 2006; Clewis et al. 2001). Weaver (2001) found yield decreases in corn and soybean from common ragweed. Corn yields decreased 38% in the presence of 32 common ragweed plants m^{-2} and in soybean, 30 common ragweed plants m^{-2} reduced yields 65 to 70% (Weaver 2001). In 1998, Clewis and others (2001) observed peanut yield losses of 1,760 kg ha^{-1} per kg increase of common ragweed biomass m^{-1}. Common ragweed competition can also impact cotton yield. North Carolina researchers reported 0.33 plants m^{-1} reduced cotton yield up to 12% (Byrd and Coble 1991).

Glyphosate and ALS-inhibiting herbicides once controlled common ragweed (Ganie and Jhala 2017). Glyphosate has been called a "once-in-a-century herbicide" (Duke and Powles 2008). When first introduced, the chemical industry felt the threat of glyphosate-resistance was considered minimal due to little residual activity, mode of action, and lack of plant metabolism of the herbicide (Bradshaw et al. 1997). However, over-reliance on glyphosate and ALS-inhibiting herbicides resulted in common ragweed biotypes resistant to these herbicides (Duke and Powles 2008; Powles and Preston 2006; Powles and Yu 2010). Common ragweed resistant to cloransulam-methyl and imazethapyr (both ALS-inhibiting herbicides) was confirmed in Indiana and Illinois in 1998 (Heap 2018; Patzoldt et al. 2001). Just a few years later, Ohio researchers reported cloransulam-methyl controlled ALS-susceptible common ragweed >80% compared to 20% control of an ALS-resistant biotype (Taylor et al. 2002). Glyphosate-resistant common ragweed was first noted in a soybean crop in Missouri and Arkansas during 2004 (Brewer & Oliver 2009; Heap 2018). In a study analyzing common ragweed control by glyphosate, Ganie and Jhala (2017) observed at least 90% control of susceptible biotypes whereas resistant biotypes were controlled 40% or less. Currently, common ragweed biotypes resistant to glyphosate and ALS-inhibiting herbicides are confirmed in 16 and 10 U.S. states, respectively (Heap 2018). Additionally, due to subsequent selection, common ragweed biotypes that have developed multiple resistance to glyphosate and ALS-inhibiting herbicides are widespread (Heap 2018).

Prior to the commercialization of glyphosate-resistant soybean, PPO-inhibiting herbicides were commonly used to control common ragweed and other broadleaf weeds (Osteen and Fernandez-Cornejo 2016; Rousonelos et al. 2012). To control common ragweed biotypes resistant to glyphosate and ALS-inhibiting herbicides, soybean producers have reverted to PPO-inhibiting herbicides once again (Reiofeli et al. 2016). In a 2012 survey of herbicide use in soybean, flumioxazin was applied to 11% of planted acres (USDA 2013). A few years later, the same survey reported fomesafen and sulfentrazone were applied to 16 and 17% of soybean planted acres surveyed, respectively (USDA 2016). In 2017, use of sulfentrazone and fomesafen application to soybean acres increased to 22% and 19%, respectively (USDA 2018). Flumioxazin, fomesafen, and sulfentrazone are all PPO-inhibiting herbicides and often two or more of these herbicides are used in a single season (Rousonelos et al. 2012; Thomas-Murphy 2018). Due to the effectiveness against glyphosate- and ALS-resistant common ragweed, flumioxazin applied preplant (PP) burndown or PRE followed by fomesafen applied POST is one such program (Thomas-Murphy 2018). Mahoney and others (2014) reported flumioxazin PP at 71 g ai ha^{-1} controlled common ragweed approximately 87% four weeks after treatment (WAT) in conventional-tillage soybean. Ohio researchers observed fomesafen and lactofen, applied POST controlled common ragweed 87 to 100% and 78 to 100% 4 WAT, respectively (Taylor et al. 2002). However, soybean producers are concerned with selecting for PPO-resistant common ragweed in response to using multiple PPO-inhibiting herbicides in a single season. Fueling their wariness is development of common ragweed biotypes resistant to PPO-inhibiting herbicides in Delaware, Maryland, Michigan, New Jersey, North Carolina, and Ohio. Furthermore, three of these states have biotypes resistant to glyphosate, ALS-, and PPO-inhibiting herbicides (Heap 2018).

Over reliance on PPO-inhibiting herbicides to control common ragweed in soybean will continue to select for PPO-resistant biotypes (Reiofeli et al. 2016). To avoid PPO-resistance it is essential to utilize several management practices, including rotating herbicide modes of action or using herbicide combinations with overlapping weed control spectrums that effectively control the target species (Evans et al. 2015; Vencill et al. 2012). The objectives of this study were to evaluate residual alternatives to the PPO-inhibiting herbicides and residual herbicide combinations, with or without PPO-inhibiting herbicides, for common ragweed control.

Materials and Methods

Experiments were conducted near Painter, Virginia at the Eastern Shore AREC (37.58942°, -75.82356°) and Suffolk, Virginia at the Tidewater AREC (36.68374°, -76.75785°) during 2017 and two separate fields at the Eastern Shore AREC (37.58952°, -75.82308° and 37.59066°, -75.82362°) during 2018. Soils included Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludults) with 1% organic matter (OM) and pH 6.4 at Painter and a Suffolk loamy sand (fine-loamy, siliceous, semiactive, thermic Typic Hapludults) with 0.9% OM and pH 6.3 at Suffolk. Experiments were established in fields with an endemic population of common ragweed. Common ragweed density averaged 95 and 1.14 plants m^{-2} at Painter and Suffolk, respectively.

Soybean were planted into conventionally prepared land (plowed and cultivated) at Painter whereas soybean were planted following strip-tillage at Suffolk. Seeding rate at Painter was 371,000 seeds ha^{-1} and 413,000 seeds ha^{-1} at Suffolk. Glufosinate-resistant soybean cultivars 'CZ478LL' (Bayer CropScience, Research Triangle Park, NC) and 'CZHBK4953LL' (Bayer CropScience, Research Triangle Park, NC) were planted on May 4 and May 17, 2017 at Painter and Suffolk, respectively. Glufosinate-resistant soybean cultivar 'CZ 4818LL' (Bayer CropScience, Research Triangle Park, NC) was planted at two separate fields near Painter on May 9, 2018 and June 6, 2018, respectively. Planting dates are listed in Table 13. The experimental design was a randomized complete block with treatments replicated four times. Plot size was four rows by 6 m long on 76 cm spaced rows at Painter and four rows by 9 m long on 91 spaced cm rows at Suffolk.

Preemergence herbicide treatments were applied immediately after planting. Herbicide application rates and sources are listed in Table 14. A nontreated check was also included. Treated plots received glufosinate POST at 42 days after planting (DAP) in 2017 and 37 and 32

DAP in 2018. In Painter, herbicides were applied using a tractor mounted sprayer with XR8003 (TeeJet Technologies, Wheaton, IL) flat fan nozzles, delivering 221 L ha^{-1} at 207 kPa. Herbicides in Suffolk were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1}. Preemergence treatments at Suffolk were applied using TTI110015 (TeeJet Technologies, Wheaton, IL) flat fan nozzles at 172 kPa whereas POST applications were made using AIXR11002 (TeeJet Technologies, Wheaton, IL) flat fan nozzles at 234 kPa.

At both locations, visible estimates of common ragweed control and soybean injury (growth reduction, chlorosis, necrosis, and total injury recorded separately) were collected according to Frans et al. (1986) 14, 28, 42, 56, and 70 DAP. Common ragweed densities were determined by counting the number of plants per 3 row middles (25 m^2) at Suffolk and plants 1 m^{-2} at Painter approximately 1 week prior to and after POST. The center two rows of plots were harvested during mid-November in 2017 and mid-October in 2018, using a small plot combine to determine soybean yield.

Data for soybean injury, weed control, common ragweed density, and soybean yield were subjected to analysis of variance (ANOVA) using JMP PRO 13 (SAS Institute Inc., Cary, NC). Treatment was treated as a fixed effect whereas location and replication was treated as random.

Results and Discussion

Soybean Response. Soybean injury was mostly observed in the form of growth reduction and necrosis. Soybean growth reduction and necrosis were combined to report total injury. Soybean injury data was pooled across location. Soybean injury was greatest early in the season 14 DA-PRE (Table 15). At this rating interval, flumioxazin containing treatments were most injurious, resulting in 16 to 19% injury. Injury caused by all other treatments at this time was 1% or less. Some injury was still observed 28 DA-PRE. At this time, linuron + clomazone injured soybean 13% (growth reduction and chlorosis). Treatments causing similar injury included metribuzin + linuron and flumioxazin + metribuzin. By 42 DA-PRE, total soybean injury was minimal and all treatments resulted ≤2% injury 42 DA-PRE. Mahoney and others (2014) observed similar injury to soybean by flumioxazin. Flumioxazin applied at 89 g ha^{-1} injured soybean 1 to 19% 4 weeks after treatment (WAT), however by 8 WAT soybean injury differences were undetectable between treated and nontreated soybean (Mahoney et al. 2014). In a study observing the soybean response to various residual herbicides, Salzman and Renner (1992) saw an increase in soybean injury with clomazone + metribuzin or linuron compared to linuron or metribuzin applied alone.

Common Ragweed Control. The two-way interaction of herbicide treatment by location was significant for common ragweed control 14 and 28 DA-PRE; hence, data for common ragweed control at these rating intervals are presented by location.

Herbicide treatments containing flumioxazin controlled common ragweed well 14 DA-PRE (Table 16). Flumioxazin, flumioxazin + metribuzin, flumioxazin + linuron, and flumioxazin + clomazone controlled common ragweed 96% to 100% across all locations. Common ragweed control by other herbicide treatments was more variable. Fomesafen and fomesafen combinations controlled the weed 80 to 90% 14 DA-PRE at Painter 2017 and 80 to 100% at Suffolk 2017. The same treatments controlled common ragweed 98 to 100% at both Painter locations during 2018. At Painter 2017, the only treatment containing metribuzin to control common ragweed greater than 80% was flumioxazin + metribuzin. Metribuzin alone, metribuzin + linuron, metribuzin + clomazone, and metribuzin + fomesafen controlled the weed 45, 64, 75, and 80% 14 DA-PRE at Painter 2017. Linuron and clomazone combined with metribuzin controlled common ragweed greater than metribuzin alone at Painter 2017 and Painter Field 2 2018. Despite improving efficacy of metribuzin when tank-mixed, linuron (63%) and clomazone (73%) applied alone did not effectively control common ragweed at Painter 2017, where common ragweed was densest. The combination of linuron + clomazone was moderately effective, controlling common ragweed 78 to 89% across all locations 14 DA-PRE.

Common ragweed control was less 28 DA-PRE. Similar to 14 DA-PRE, flumioxazin alone and flumioxazin combinations were most effective. These treatments controlled common ragweed 95% or greater across all locations (Table 17). Herbicide treatments including fomesafen controlled the weed 80 to 94%, 91 to 98%, 100%, and 98 to 100% 28 DA-PRE at Painter 2017, Suffolk 2017, Painter Field 1 2018, and Painter Field 2 2018, respectively. Similar to observations earlier in the season, herbicide treatments that did not include a PPO-inhibiting herbicide did not effectively control common ragweed at Painter 2017. At this location, only linuron + clomazone controlled common ragweed greater than 78%. At the same time, metribuzin + linuron and metribuzin + clomazone controlled common ragweed 89 and 93%, respectively and were more effective than metribuzin, linuron, clomazone, and linuron + clomazone. Van Wely and others (2015) observed >80% common ragweed control 4 and 8 weeks after application with linuron and metribuzin. Similarly, Ackley and others (1997) found an increase in common ragweed control when metribuzin or linuron was combined with *S*-metolachlor. Common ragweed control by clomazone when preplant incorporated (PPI) has been noted, Jordan et al (1994) observed 91% control when clomazone was applied 0.8 kg ha^{-1}.

Common ragweed density mirrored common ragweed control. Common ragweed density was greatest at Painter 2017. Density in nontreated check plots averaged 274 plants m^{-2} 22 DAP (Table 18). All herbicide treatments reduced common ragweed density compared to the nontreated check at Painter 2017. At the same location, relative to the nontreated check, residual herbicide treatments including flumioxazin reduced common ragweed density 95 to 99% whereas fomesafen containing treatments reduced density of the weed 85 to 92%. With the exception of linuron + clomazone (86%), herbicide treatments not including a PPO-inhibiting herbicide only reduced common ragweed density 39 to 75% at Painter 2017. Common ragweed density at all other locations was much less. At Suffolk 2017 and Painter Field 2 2018, metribuzin alone did not reduced common ragweed density compared to the nontreated check. Other herbicide treatments reduced common ragweed density 60 to 100% across Suffolk 2017, Painter Field 1, 2018, and Painter Field 2 2018. The rate of metribuzin used in these experiments was 280 g ai ha^{-1} and was chosen based on the coarse-textured soils present at each location. Metribuzin can exacerbate injury on coarse-textured soils with low organic matter (Anonymous 2009; Green et al. 1988). The relative low rate of metribuzin used for this study may explain why common ragweed control and density reduction by metribuzin was poor.

Glufosinate was applied POST when soybean averaged 4 trifoliate and controlled 24 cm common ragweed well. Common ragweed control 14, 28, and 42 DA-POST by all residual herbicide treatments fb glufosinate POST was 99 to 100% (Table 19). Beyers et al. (2002) achieved >85% control of common ragweed and other weed species by glufosinate, there was also an increase in control when glufosinate was applied following pendimethalin, sulfentrazone, cloransulam-methyl or flumioxazin. Common ragweed density was also reduced by glufosinate (≤ 1 plant m^{-2}) regardless of PRE (Table 20). Common ragweed is typically one of the first weeds to germinate during the spring (Myers et al. 2004; Werle et al. 2014). It is likely that most common ragweed had emerged prior to glufosinate being applied POST. Because glufosinate effectively controls emerged common ragweed (Barnes et al. 2017; Wilson et al. 1985) and the weed is unlikely to emerge later in the season. This explains why common ragweed control late in the season was excellent despite poor early season common ragweed control by some treatments like metribuzin alone.

Annual Grass Control. Annual grasses evaluated included Texas millet (*Urochloa texana* Buckl.), large crabgrass (*Digitaria* sanguinalis (L.) Scop.), and foxtail species (*Setaria* spp.). Residual herbicide treatments containing clomazone controlled annual grasses 96% or greater 14 DA-PRE (Table 21). Treatments including flumioxazin (95 to 98%) controlled annual grass similar to clomazone whereas fomesafen (87%), metribuzin (68%), linuron (86%), and metribuzin + linuron (88%) were less effective 14 DA-PRE. A similar trend was observed 28 DA-PRE. Clomazone, flumioxazin + clomazone, fomesafen + clomazone, metribuzin + clomazone, and linuron + clomazone controlled annual grasses 90% or greater 28 DA-PRE. Again, fomesafen alone, metribuzin alone, and linuron alone were least effective controlling annual grasses. Annual grass activity by clomazone is well documented (Jordan et al. 1994; Westberg 1989). Jordan and others (1994) observed control of fall panicum and large crabgrass by at least 95% with clomazone PPI. At a lower rate than used in this experiment, clomazone controlled several annual grasses 90 to 100% at 280 g ai ha^{-1} (Westberg et al. 1989)

Like common ragweed, annual grass control improved following glufosinate applied POST. Although glufosinate is less effective than glyphosate for annual grass control, glufosinate can be effective if applied when annual grasses are small ($\leq$ 10 cm) (Corbett et al. 2004). All herbicide treatments, following glufosinate applied POST, controlled annual grasses 89% or greater and 81% or greater 28 and 42 DA-PRE, respectively (Table 22).

Soybean yield. Soybean yield in nontreated plots averaged 2038 kg ha^{-1} (Table 23). All herbicide treatment improved soybean yield compared to the nontreated; however, few differences in soybean yield were noted across treated plots. Soybean yield treated with a PRE herbicide fb glufosinate POST ranged 3527 to 4210 kg ha^{-1}. Other researchers have also seen a yield increase with PRE fb POST (Legleiter et al. 2009). This yield increase may be due to reduced early season weed competition through PRE control (Legleiter et al. 2009).

In general, flumioxazin and fomesafen, the PPO-inhibiting herbicides used for these experiments, were more effective for common ragweed control than metribuzin, linuron, and clomazone. However, in some instances, combinations of two non-PPO-inhibiting herbicides, like linuron + clomazone were similarly effective as flumioxazin and fomesafen. Furthermore, combinations of a PPO-inhibiting herbicide + non-PPO controlled common ragweed similar to the PPO-inhibiting herbicides alone. Herbicide combinations are useful in avoiding herbicide resistance (Norsworthy et al. 2012). Results from these experiments suggest soybean producers concerned with selecting for PPO-resistant common ragweed can effectively delay resistance by using residual combinations of non-PPO-inhibiting herbicides at soybean planting. Alternatively, instead of abandoning the PPO-inhibiting herbicides, producers can use a non-PPO herbicide that effectively controls common ragweed in combination with flumioxazin or fomesafen and reduce the risk of herbicide resistance.

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Tables

Table 13. Planting and herbicide application dates.

Location	**Year**	**Planting Date**	**Herbicide application date**	
			PRE	**POST**
Painter	2017	May 4	May 4	June 14
Suffolk	2017	May 17	May 17	June 14
Painter Field 1	2018	May 9	May 9	June 14
Painter Field 2	2018	June 6	June 6	July 9

Table 14. Herbicides used in experiments.[a]

Treatment	Trade Names	Application Rate (g ai ha^{-1})	Formula Concentration	Manufacturer
flumioxazin	Valor ® SX	107 g ai	51%	Valent U.S.A. Corp.
fomesafen	Reflex®	420 g ai	240 g ai L^{-1}	Syngenta Crop Protection
metribuzin	TriCor 75 DF ®	280 g ai	75%	United Phosphorous, Inc.
linuron	Linex® 4L	981 g ai	479 g ai L^{-1}	Tessenderlo Kerley, Inc.
clomazone	Command® 3ME	526 g ai	359 g ai L^{-1}	FMC Corporation
glufosinate	Liberty ® 280	656 g ai	280 g ai L^{-1}	Bayer CropScience

[a] Product labels, mailing addresses, and web site addresses can be found at www.cdms.net.

Table 15. Soybean injury 14, 28, and 42 days after (DA) preemergence (PRE) herbicides applied at soybean planting in Virginia. [a,b]

PRE[c]	Soybean injury (%)		
	14 DA-PRE	28 DA-PRE	42 DA-PRE
flumioxazin	17 bc	5 c-f	1 b
flumioxazin + metribuzin	19 a	11 ab	2 b
flumioxazin + linuron	19 ab	8 bcd	2 b
flumioxazin + clomazone	16 c	6 c-f	0 b
fomesafen	0 d	3 ef	1 b
fomesafen + metribuzin	0 d	6 c-f	0 b
fomesafen + linuron	1 d	5 c-f	1 b
fomesafen + clomazone	0 d	7 cde	1 b
metribuzin	0 d	3 ef	1 b
metribuzin + linuron	1 d	12 ab	1 b
metribuzin + clomazone	0 d	4 def	0 b
linuron	1 d	8 bc	1 b
clomazone	0 d	2 f	0 b
linuron + clomazone	1 d	13 a	5 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates and sources are listed in Table 14.

Table 16. Common ragweed control 14 days after (DA) preemergence (PRE) herbicides applied at planting. [a]

PRE[b]	Common ragweed control 14 DA-PRE (%)			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	99 a	100 a	100 a	100 a
flumioxazin + metribuzin	96 a	100 a	100 a	100 a
flumioxazin + linuron	96 a	100 a	100 a	100 a
flumioxazin + clomazone	98 a	100 a	100 a	100 a
fomesafen	81 bc	100 a	100 a	98 a
fomesafen + metribuzin	80 bc	85 a	100 a	100 a
fomesafen + linuron	90 ab	100 a	100 a	100 a
fomesafen + clomazone	84 bc	80 a	98 a	100 a
metribuzin	45 f	78 a	100 a	75 d
metribuzin + linuron	64 de	100 a	96 a	95 ab
metribuzin + clomazone	75 cd	100 a	100 a	98 a
linuron	63 e	65 a	96 a	86 c
clomazone	73 cde	65 a	94 a	90 bc
linuron + clomazone	89 ab	100 a	78 b	75 d

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates and sources are listed in Table 14.

Table 17. Common ragweed control 28 days after (DA) preemergence (PRE) herbicides applied at soybean planting. [a]

PRE[b]	Common ragweed control 28 DA PRE (%)			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	96 a	98 a	100 a	100 a
flumioxazin + metribuzin	95 a	98 a	100 a	100 a
flumioxazin + linuron	95 a	96 a	100 a	100 a
flumioxazin + clomazone	98 a	98 a	100 a	100 a
fomesafen	83 bcd	91 ab	100 a	98 ab
fomesafen + metribuzin	80 cde	91 ab	100 a	98 ab
fomesafen + linuron	94 ab	98 a	100 a	100 a
fomesafen + clomazone	88 abc	91 ab	100 a	100 a
metribuzin	45 f	20 d	50 c	53 d
metribuzin + linuron	70 e	64 bc	100 a	89 b
metribuzin + clomazone	78 cde	81 abc	100 a	93 ab
linuron	74 de	77 abc	100 a	68 c
clomazone	71 de	62 c	89 b	70 c
linuron + clomazone	87 abc	95 a	100 a	70 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Herbicide use rates and sources are listed in Table 14.

Table 18. Common ragweed densities prior to glufosinate applied postemergence in response to residual herbicides.[a]

PRE[b]	Common ragweed density (plants m^{-2})			
	Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	6 g	0 b	0 c	0 c
flumioxazin + metribuzin	15 efg	0 b	0 c	0 c
flumioxazin + linuron	11 fg	0 b	0 c	0 c
flumioxazin + clomazone	3 g	0 b	0 c	0 c
fomesafen	26 d-g	0 b	0 c	0 bc
fomesafen + metribuzin	35 c-g	0 b	0 c	0 c
fomesafen + linuron	6 g	0 b	0 c	0 c
fomesafen + clomazone	42 c-g	0 b	0 c	0 c
metribuzin	168 b	1 a	2 b	5 a
metribuzin + linuron	73 cde	0 b	0 c	1 bc
metribuzin + clomazone	69 c-f	0 b	0 c	0 c
linuron	93 c	0 b	0 c	2 bc
clomazone	81 cd	0 b	1 bc	2 b
linuron + clomazone	39 c-g	0 b	0 c	1 bc
nontreated	274 a	1 a	5 a	6 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates and sources are listed in Table 14.

Table 19. Common ragweed control by preemergence (PRE) herbicides followed by glufosinate applied postemergence (POST), 14, 28, and 42 days after (DA) POST in Virginia. [ab]

PRE[c]	POST[d]	Common ragweed control (%)		
		14 DA-POST	28 DA-POST	42 DA-POST
flumioxazin	glufosinate	100 a	100 a	100 a
flumioxazin + metribuzin	glufosinate	100 a	100 a	100 a
flumioxazin + linuron	glufosinate	100 a	100 a	100 a
flumioxazin + clomazone	glufosinate	100 a	100 a	100 a
fomesafen	glufosinate	100 a	100 a	100 a
fomesafen + metribuzin	glufosinate	100 a	100 a	100 a
fomesafen + linuron	glufosinate	100 a	100 a	100 a
fomesafen + clomazone	glufosinate	100 a	100 a	100 a
metribuzin	glufosinate	99 b	99 ab	99 a
metribuzin + linuron	glufosinate	100 a	100 ab	100 a
metribuzin + clomazone	glufosinate	100 a	99 ab	99 a
linuron	glufosinate	100 a	100 ab	99 a
clomazone	glufosinate	100 a	99 b	99 a
linuron + clomazone	glufosinate	100 a	100 ab	99 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates and sources are listed in Table 14.

[d] Glufosinate applied at 656 g ai ha^{-1} to 4-trifoliate soybean and 24 cm tall common ragweed.

Table 20. Common ragweed densities in response to preemergence (PRE) herbicides followed by glufosinate applied postemergence.[a]

PRE[b]	POST[c]	Common ragweed density (plants m^{-2})			
		Painter 2017	Suffolk 2017	Painter Field 1 2018	Painter Field 2 2018
flumioxazin	glufosinate	0 b	0 b	0 b	0 b
flumioxazin + metribuzin	glufosinate	0 b	0 b	0 b	0 b
flumioxazin + linuron	glufosinate	0 b	0 b	0 b	0 b
flumioxazin + clomazone	glufosinate	0 b	0 b	0 b	0 b
fomesafen	glufosinate	0 b	0 b	0 b	0 b
fomesafen + metribuzin	glufosinate	0 b	0 b	0 b	0 b
fomesafen + linuron	glufosinate	0 b	0 b	0 b	0 b
fomesafen + clomazone	glufosinate	0 b	0 b	0 b	0 b
metribuzin	glufosinate	1 b	0 b	0 b	0 b
metribuzin + linuron	glufosinate	0 b	0 b	0 b	0 b
metribuzin + clomazone	glufosinate	0 b	0 b	0 b	0 b
linuron	glufosinate	0 b	0 b	0 b	0 b
clomazone	glufosinate	0 b	0 b	0 b	0 b
linuron + clomazone	glufosinate	0 b	0 b	0 b	0 b
nontreated		274 a	1 a	5 a	5 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide use rates and sources are listed in Table 14.

[c] Glufosinate applied at 656 g ai ha^{-1} to 4-trifoliate soybean and 24 cm tall common ragweed.

Table 21. Annual grass control 14 and 28 days after (DA) preemergence (PRE) herbicides applied at soybean planting in Virginia. [a,b]

PRE[c]	Annual grass control (%)[d]	
	14 DA-PRE	28 DA-PRE
flumioxazin	95 a	87 b-e
flumioxazin + metribuzin	98 a	96 a
flumioxazin + linuron	98 a	94 ab
flumioxazin + clomazone	98 a	96 a
fomesafen	87 bc	82 de
fomesafen + metribuzin	93 ab	83 cde
fomesafen + linuron	93 ab	90 ab
fomesafen + clomazone	96 a	95 a
metribuzin	68 d	63 f
metribuzin + linuron	88 bc	87 bcd
metribuzin + clomazone	99 a	97 a
linuron	86 c	79 e
clomazone	96 a	90 abc
linuron + clomazone	99 a	96 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates and sources are listed in Table 14.

[d] Annual grasses consisted of Texas millet, large crabgrass, and foxtail species.

Table 22. Annual grass control by preemergence (PRE) herbicides followed by glufosinate applied postemergence (POST), 14, 28, and 42 days after (DA) POST, in Virginia. [a,b]

PRE[c]	POST[d]	Annual grass control (%)[e]		
		14 DA-POST	28 DA-POST	42 DA-POST
flumioxazin	glufosinate	95 ab	97 a	96 abc
flumioxazin + metribuzin	glufosinate	98 a	96 a	96 abc
flumioxazin + linuron	glufosinate	97 ab	96 a	96 ab
flumioxazin + clomazone	glufosinate	98 a	99 a	99 ab
fomesafen	glufosinate	81 d	95 ab	93 bcd
fomesafen + metribuzin	glufosinate	80 d	97 a	96 ab
fomesafen + linuron	glufosinate	82 cd	98 a	95 abc
fomesafen + clomazone	glufosinate	96 ab	99 a	97 ab
metribuzin	glufosinate	64 e	89 c	81 e
metribuzin + linuron	glufosinate	82 cd	90 bc	88 d
metribuzin + clomazone	glufosinate	99 a	99 a	98 ab
linuron	glufosinate	85 cd	96 a	90 cd
clomazone	glufosinate	89 bc	97 a	94 a-d
linuron + clomazone	glufosinate	98 a	97 a	99a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates and sources are listed in Table 14.

[d] Glufosinate applied at 656 g ai ha^{-1} to 4-trifoliate soybean and 24 cm tall common ragweed.

[e] Annual grasses consisted of Texas millet, large crabgrass, and foxtail species.

Table 23. Soybean yield in response to preemergence (PRE) herbicides followed by glufosinate applied postemergence, in Virginia.[a,b]

PRE[c]	POST[d]	Soybean Yield (kg ha^{-1})
flumioxazin	glufosinate	3964 ab
flumioxazin + metribuzin	glufosinate	4013 ab
flumioxazin + linuron	glufosinate	3793 ab
flumioxazin + clomazone	glufosinate	3994 ab
fomesafen	glufosinate	3899 ab
fomesafen + metribuzin	glufosinate	4210 a
fomesafen + linuron	glufosinate	3889 ab
fomesafen + clomazone	glufosinate	4002 ab
metribuzin	glufosinate	3527 b
metribuzin + linuron	glufosinate	4014 ab
metribuzin + clomazone	glufosinate	4079 ab
linuron	glufosinate	3749 ab
clomazone	glufosinate	3865 ab
linuron + clomazone	glufosinate	4058 ab
nontreated		2038 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide use rates and sources are listed in Table 14.

[d] Glufosinate applied at 656 g ai ha^{-1} to 4-trifoliate soybean.

Alternatives to Multiple Protoporphyrinogen Oxidase Inhibiting Herbicides for Control of Common Ragweed (*Ambrosia artemisiifolia*) and Palmer Amaranth (*Amaranthus palmeri*) in Soybean

Abstract

Common ragweed and Palmer amaranth both contaminate soybean resulting in yield reduction. While glyphosate and acetolactate synthase (ALS)-inhibiting herbicides once controlled both weeds, biotype resistant to these herbicides have evolved. Currently soybean producers rely on protoporphyrinogen oxidase (PPO)-inhibiting herbicides to control herbicide-resistant common ragweed and Palmer amaranth. A popular soybean herbicide program includes flumioxazin applied preemergence (PRE) followed by (fb) fomesafen applied postemergence (POST), both PPO-inhibiting herbicides. Over reliance on PPO-inhibiting herbicides has placed intense selection pressure on common ragweed and Palmer amaranth, resulting in PPO resistance. The objective of this experiment was to compare common ragweed and Palmer amaranth control in systems utilizing zero, one, or two PPO-inhibitors in a growing season. Common ragweed and Palmer amaranth were controlled completely by flumioxazin 14 days after planting (DAP). Acetochlor and linuron controlled common ragweed <74%, yet controlled Palmer amaranth >96%. Clomazone and metribuzin were weaker (<85%) on both weeds 14 DAP. Fomesafen POST controlled both weeds greater than glufosinate POST. Regardless of PRE herbicide treatment, when a residual herbicide was followed by (fb) glufosinate or fomesafen POST, common ragweed was controlled by at least 95% and Palmer amaranth 80%. To reduce PPO selection pressure, soybean producers growing glufosinate-resistant soybean may use flumioxazin PRE fb glufosinate POST whereas non-Liberty-Link growers should save their PPO herbicide for POST and use a non-PPO herbicide PRE such as linuron or acetochlor.

Alternatively, these producers can effectively reduce PPO selection pressure by implementing residual combinations of a PPO-inhibiting herbicide + non-PPO weed control spectrums that overlap at either Palmer amaranth or common ragweed.

Introduction

Common ragweed and Palmer amaranth have presented many issues in several crops including soybean. Common ragweed (*Ambrosia artemisiifolia* L.) is broadleaf weed harming soybean and many other crops (Ganie and Jhala 2017). Native to North America, the branching and erect summer annual weed can grow to a height of up to 2 m and has a fibrous root system (Bryson and DeFelice 2009). Common ragweed is one of the first summer annual weeds to emerge in the spring (Myers et al. 2004; Stoller and Wax 1973; Uva et al. 1997). Myers et al. (2004) found that when comparing eight weed species, common ragweed emerged by mid to late May, prior to most other species. Although common ragweed emerged early, it also had the shortest emergence period (Myers et al. 2004). Common ragweed is monecious, having male and female flowers on a single plant, but is largely self-incompatible (Friedman and Barrett 2008). The ability to outcross increases genetic diversity which in turn increases the likelihood of herbicide resistance (Friedman and Barrett 2008; Uva et al. 1997). A single common ragweed plant is capable of producing 32,000 to 62,000 seed (Davis et al. 2014).

Common ragweed is capable of reducing yield of several crops (Chikoye et al. 1995; Clay et al. 2006; Clewis et al. 2001; Coble et al. 1981; Cowbrough et al. 2003; Weaver 2001). Weaver (2001) found a 38% yield decrease in corn, with 32 plants m^{-2}. Peanut (*Arachis hypogaea* L.) also suffers yield losses from common ragweed, just one common ragweed plant m^{-1} row can result in 40% yield reduction (Clewis et al. 2001). Soybean yields can be reduced by 65 to 70% with 30 common ragweed plants m^{-2} (Weaver 2001). In addition to yield losses, common ragweed has also shown interference with other bean crop harvest (Chikoye et al. 1995).

Due to Palmer amaranth's (*Amaranthus palmeri* S. Wats.) competitiveness, adaptability and prolific seed production it is one of the most troublesome and well noted weeds (Ehleringer 1983; Monks and Oliver 1988; Place et al. 2008; Ward et al. 2013; Wright et al. 1999). Attributes to Palmer amaranth's competitiveness and adaptability include drought tolerance, rapid growth, and shade tolerance (Ehleringer 1983; Jha et al. 2008; Monks and Oliver 1988; Noguchi 1992; Sauer 1955; Sosnoskie et al. 2014). Just one female plant is capable of producing one million seeds under proper growing conditions (Sosnoskie et al. 2014). Soybean, corn, and cotton yields are reduced when in competition with Palmer amaranth (Culpepper et al. 2010; Flessner et al. 2016; MacRae et al. 2008; Massigna et al. 2003; Morgan et al. 2001; Rowland et al. 1999; Webster 2009). Klingaman and Oliver (1994) observed a 68% yield reduction in soybean with 10 Palmer amaranth plants in m^{-1} of row.

Acetolactate synthase (ALS)-inhibiting herbicides and glyphosate once provided excellent common ragweed and Palmer amaranth control (Rousonelos et al. 2012). However, over reliance on these herbicides to control common ragweed and Palmer amaranth selected for ALS- and glyphosate-resistant biotypes (Bond et al. 2006; Corbett et al. 2004; Duke and Powles 2008; Powles and Preston 1995; Powles and Yu 2010). Palmer amaranth biotypes resistant to ALS-inhibiting herbicides were first confirmed in 1993 and shortly thereafter an ALS-resistant common ragweed biotype was found in 1998 (Heap 2018). In 1996, glyphosate-resistant soybean were commercialized, transforming weed control (Wilcut et al. 1995; Young 2006). Glyphosate is an 5-enolpyruvylshikimate-3-phosphate synthase (EPSP)-synthase inhibitor with broad-spectrum activity (Baird et al. 1971; Dill et al. 2010). Widespread adoption of glyphosate-resistant crops such as soybean and cotton reduced the use of other modes of action (MOA)s such as ALS- and PPO-inhibiting herbicides (Kniss 2018; Osteen and Fernandez-Cornejo 2016).

Furthermore, with the ability to control most weeds POST with glyphosate, many growers decreased use of residual herbicides applied preplant or PRE (Young 2006). The first confirmed case of glyphosate-resistance was rigid ryegrass (*Lolium rigidum* Gaud.) in 1996 (Heap 2018; Powles et al. 1998). Since then, several glyphosate-resistant weeds have been identified including goosegrass (*Eleusine indica* (L.) Gaertn.), horseweed (*Conyaza canadenis* L.), Italian ryegrass (*Lolium perenne ssp. multiflorum*), giant ragweed (*Ambrosia trifida* L.), and several more (Baerson et al. 2002; Barnes et al. 2017; Heap 2018; Jasieniuk et al. 2008; Stoltenberg et al. 2012; VanGessel 2001). There are now 42 weed species with confirmed glyphosate-resistant biotypes and many of these biotypes are also resistant to ALS-inhibiting herbicides (Heap 2018)

Glyphosate and ALS-resistant weeds forced producers to find alternative sites of action (SOA) and methods of weed control (Sosnoskie and Culpepper 2014; Whitaker et. al 2011). One such SOA in soybean and other crops was Protoporphyrinogen oxidase (PPO) inhibiting herbicides (Whitaker et al. 2011). Protoporphyrinogen oxidase-inhibiting herbicides can be separated into many herbicide families such as diphenylether, N-phenylphthalimide, pyrimidinedione and aryl triazone, most commonly used in soybean since their introduction in the 1960s (Salas et al. 2016). Effectiveness of PPO-inhibiting herbicides and widespread glyphosate- and ALS-resistant weeds increased reliance on PPO-inhibiting herbicides (Sosnoskie and Culpepper 2014). Prior to glyphosate resistance, flumioxazin used as a burndown application and fomesafen as PRE were only applied to 3 and 4% of cotton acres, use of these two products saw a ten-fold increase after glyphosate-resistance (Sosnoskie and Culpepper 2014). Whitaker et al. (2011) found flumioxazin and fomesafen to control Palmer amaranth biotypes resistant to glyphosate and ALS-inhibiting herbicides better than other residual herbicides. Multiple applications of PPO-inhibiting herbicides are not uncommon in soybean production (Thomas-Murphy 2018). Specifically, flumioxazin applied preplant or PRE followed by fomesafen applied POST, both of which are PPO-inhibiting herbicides, is a popular soybean herbicide program where glyphosate- and ALS-resistant weeds dominate (Rousonelos et al. 2012). Application of two or more herbicides with the same SOA within a single growing season places intensely selects for weeds with resistance, commonly called selection pressure (Hanson et al. 2013; Reiofeli et al. 2016).

In response to intense PPO-selection pressure, tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer), closely related to Palmer amaranth, first evolved resistance to PPO-inhibiting herbicides in 2001 (Heap 2018; Shoup 2003). Target site mutation in the *PPX2* gene was confirmed to confer PPO-resistance in common ragweed, Palmer amaranth, and tall waterhemp (Patzoldt et al. 2006; Rousonelos et al. 2012; Varanasi et al. 2018). Cases of resistance has increased to 13 species with resistance to PPO-inhibitors including common ragweed and Palmer amaranth (Heap 2018). There is common ragweed with confirmed resistance to PPOs in six states (Delaware, Michigan, New Jersey, North Carolina, Maryland, and Ohio) and Palmer amaranth in several states including Arkansas, Illinois, and Tennessee, as well as suspected in others across the Southern U.S. (Heap 2018). Soybean producers relying on two or more PPO-inhibiting herbicides annually are growing concerned with selecting for PPO-resistant common ragweed and Palmer amaranth (Hart 2016; Ward et al. 2013).

The objective of this study was to evaluate common ragweed and Palmer amaranth control by soybean herbicide programs utilizing zero, one, or two PPO-inhibiting herbicides, with the overarching goal of identifying effective herbicide programs that will limit PPO-selection pressure.

Materials and Methods

Experiments were conducted near Painter, Virginia at the Eastern Shore AREC (37.58933°, -75.82372°), near Suffolk, Virginia at the Tidewater AREC (36.68349°, -76.75841°)during 2017 and 2 separate fields (37.58952°, -75.82323° and 37.59122°, -75.82424°) at Painter in 2018. Soils included Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult) with 1% OM and pH 6.4 in Painter and a Suffolk loamy sand (fine-loamy, siliceous, semiactive, thermic, Typic Hapludult) with 0.9% organic matter (OM) and pH 6.3 in Suffolk. Experiments were established in fields with an endemic population of common ragweed. Common ragweed density averaged 114 and 2 plants m^{-2} at Painter 2017, Field 1 2018 and Suffolk 2017, respectively. Glyphosate-susceptible Palmer amaranth was sown at Painter Field 2 in 2018 to achieve a final density of 96 plants m^{-2}. Common ragweed was targeted at Painter 2017, Suffolk 2017, and Painter Field 1 2018; whereas Palmer amaranth was targeted at Painter Field 2 2018.

Glufosinate-resistant soybean cultivars were planted at all environments, into conventionally prepared land (plowed and cultivated) at Painter and following strip-tillage at Suffolk. Seeding rate at Painter was 371,000 seeds ha $^{-1}$ and 413,000 seeds ha $^{-1}$ at Suffolk. Soybean cultivar 'CZ4748LL' (Bayer CropScience, Research Triangle Park, NC) was planted on May 4, 2017 at Painter, whereas soybean cultivar 'CZHBK4953LL' (Bayer CropScience, Research Triangle Park, NC) was planted on May 17, 2017 at Suffolk. Glufosinate-resistant soybean cultivar 'CZ 4818LL' (Bayer CropScience, Research Triangle Park, NC) was planted at both fields near Painter in 2018 on May 9, 2018. Soybean planting dates listed in Table 24. The experimental design was a randomized complete block with four replications at both sites. Plot size included four rows by 6 m long on 76 cm spaced rows at Painter and 9 m long on 91 cm spaced rows at Suffolk.

Treatments consisted of a factorial arrangement of six PRE treatments and three POST treatments. Herbicide application rates and sources are listed in Table 25. Postemergence treatments were applied to 2- to 5-trifoliate soybean when common ragweed was $\leq$ 22 cm tall and $\leq$ 25 cm tall Palmer amaranth. Herbicides were applied using a 5 nozzle XR8003 (TeeJet Technologies, Wheaton, IL) flat fan tractor sprayer delivering 221 L ha^{-1} at 207 kPa at Painter. All herbicides at Suffolk were applied using a CO_2 pressurized backpack sprayer delivering 140 L ha^{-1}; PRE treatments were applied using 4 flat-fan nozzles TTI110015 (TeeJet Technologies, Wheaton, IL) at 234 kPA whereas POST treatments were applied using 5 flat-fan nozzles AIXR11002 (TeeJet Technologies, Wheaton, IL) at 172 kPa.

Visible estimates of common ragweed control, Palmer amaranth control, and soybean injury (0-100%) were estimated according to Frans et al. (1986) at 14, 28, 42, 56, and 70 days after planting (DAP). Common ragweed and Palmer amaranth densities were determined approximately one week prior to and after POST application by counting all common ragweed from three row middles (14 or 17 m^2) at Suffolk or m^{-2} at Painter. In 2017, all plots were harvested using a small plot combine in mid–November to determine soybean yield. In 2018, plots were unharvestable due to severe weed pressure.

Data for soybean injury, weed control, common ragweed and Palmer amaranth densities, and soybean yields were subjected to analysis of variance (ANOVA) using JMP PRO 13 (SAS Institute Inc., Cary, NC) at an alpha level of $\leq$0.05. Herbicide treatments was treated as a fixed factor whereas location and replication were treated as random.

Results and Discussion

Soybean response. Soybean injury data was pooled across location. Soybean injury from residual herbicides was greatest 14 DA-PRE. Flumioxazin injured soybean 11%; no other residual herbicides injured soybean at this time (Table 26). Injury observed was mostly in the form of growth reduction and minor necrosis, which are typical soybean responses to the herbicide (Hartzler 2017; Legleiter 2013). Soybean injury resulting from flumioxazin decreased as the season progressed and by 28 DA-PRE soybean injury totaled 6%. Flumioxazin remained more injurious than metribuzin, acetochlor, and clomazone at this time. However, linuron (10%) injured soybean, mostly in the form of chlorosis, greater than flumioxazin 28 DA-PRE. Early season soybean injury resulting from flumioxazin and linuron was transitory with minimal injury observed later in the season. In the absence of a POST herbicide, late season soybean injury from flumioxazin and linuron was 2% and 3% or less 42 to 50 and 56 to 64 d after planting, respectively (Table 27).

Fomesafen was more injurious than glufosinate when applied to 5-trifoliate soybean. In the absence of a residual herbicide applied PRE, fomesafen injured soybean 17% 14 DA-POST (Table 27). Soybean response to fomesafen has been well documented and soybean are reported to recover rapidly from fomesafen injury (Beam et al. 2018; Hager and Sprague 2000; Whitaker et al. 2010). Little soybean injury was observed in plots not receiving a POST herbicide, evidence that majority of the soybean injury observed following POST applications resulted from foliar necrosis caused by fomesafen or glufosinate. Soybean receiving a PRE herbicide followed by fomesafen injured soybean 11 to 25% whereas soybean treated with a PRE herbicide followed by glufosinate injured soybean only 1 to 6%. By 28 DA-POST, soybean had mostly recovered from earlier injury; soybean injury at this time was 8% or less. Similarly, Beam and others (2018) did not observe any significant differences in soybean yield from plots treated with fomesafen, acifluorfen, lactofen, or nontreated.

Common Ragweed Control. Common ragweed control was evaluated at both environments during 2017 and Painter Field 1 during 2018. Flumioxazin applied PRE controlled common ragweed well, controlling the weed (98%) 14 DA-PRE (Table 28). At the same time, all other residual herbicides were less effective. Linuron and clomazone were moderately effective, controlling common ragweed 73 and 79% 14 DA-PRE, respectively whereas metribuzin and acetochlor controlled the weed no greater than 49%. A similar trend for common ragweed control was observed 28 DA-PRE. Again, flumioxazin (91%) controlled common ragweed most effectively while common ragweed control by clomazone (84%), although numerically less, was statistically similar to flumioxazin 28 DA-PRE. At the same time, acetochlor, metribuzin, and linuron controlled common ragweed 45, 52, and 80%, respectively. Trends for common ragweed density closely matched common ragweed control. Seven days prior to POST, common ragweed density in nontreated check plots averaged 114 plants m^{-2} (Table 29). Flumioxazin, linuron, and clomazone reduced common ragweed density 97, 83, and 61% compared to the nontreated check, respectively. In contrast, metribuzin only reduced common ragweed density 44% whereas acetochlor had no effect on common ragweed density relative to the nontreated.

Later in the season, in the absence of a POST herbicide, flumioxazin continued to control common ragweed well. Flumioxazin applied PRE without a POST herbicide, controlled common ragweed 79 to 97% and 71 to 96% 42 to 50 and 56 to 64 d after planting (DAP), respectively (Table 30). At the same rating intervals, again without a POST herbicide, common ragweed control by metribuzin, linuron, acetochlor, and clomazone was no greater than 53%.

Results from these experiments and previous research confirms flumioxazin applied PRE controls common ragweed well. In soybean, Chandi and others (2012) observed 80% control with flumioxazin alone and 100% control when fb lactofen or glyphosate. Common ragweed control reported by other researchers ranges poor to good (Jordan et al. 2014; Scott et al. 2002). Greater than 90% common ragweed control has been documented with clomazone applied at 800 g ai ha^{-1} (Jordan et al. 1994). However, when clomazone was applied at 175 g ai ha^{-1} in combination with ethalfluralin at 630 g ai ha^{-1}, common ragweed control was no more than 40% (Trader et al. 2007). These reports indicate suggests that clomazone rate may influence common ragweed control. Clomazone rate used for these experiments was intermediate and may explain moderate common ragweed control observed. Although in this research, control with metribuzin was poor, previous research indicates metribuzin controls common ragweed well (Ackley et al. 1997; Van Wely et al. 2015). Van Wely and others (2015) observed >80% common ragweed control 4 and 8 weeks after application with linuron and metribuzin 653 g ai ha^{-1}. Additionally, metribuzin applied at 280 g ai ha^{-1} controlled common ragweed 88% (Ackley et al. 1997). In a study focusing on metribuzin rates in correlation with soil type, Peter and Weber (1985) observed an increased rate was need to control 80% of common ragweed in soils with high organic matter and clay. The rate of metribuzin used in these experiments was 262 g ai ha^{-1} and was chosen based on the coarse-textured soils present at each location. Metribuzin is capable of injuring soybean on coarse-textured soils with low organic matter (Street et al. 1987). The relative low rate of metribuzin used for these experiments may explain poor common ragweed control by the herbicide relative to other research.

Fomesafen and glufosinate applied POST greatly improved common ragweed control. Without a PRE herbicide, fomesafen and glufosinate controlled common ragweed 98 to 100% and 88% or greater 14 and 28 DA-POST, respectively (Table 31). In general, fomesafen and glufosinate controlled common ragweed similarly. However, at Painter 2017, fomesafen controlled common ragweed greater than glufosinate when applied after all PRE herbicide treatments, except flumioxazin. Fomesafen and glufosinate applied POST coupled with a residual herbicide controlled common ragweed 95 to 100% 14 DA-POST and 86 to 100% 28 DA-POST and few treatment differences were observed.

Common ragweed density 7 DA-POST in nontreated plots averaged 65, 2, and 68 plants m^{-2} at Painter 2017, Suffolk 2017, and Painter Field 1 2018, respectively (Table 29). All herbicide treatments, except metribuzin, linuron, acetochlor, and clomazone without a POST herbicide, reduced common ragweed density 72 to 100% and relative to the nontreated at Painter 2017. Similarly, the same herbicide treatments at Suffolk 2017, completely controlled common ragweed whereas metribuzin alone, linuron alone, acetochlor alone, and clomazone reduced common ragweed density no better than 50%.

Herbicide programs including two PPO-inhibiting herbicides, flumioxazin PRE followed by fomesafen POST, controlled common ragweed excellent (100%) 28 DA-POST and is consistent with previous research (Everman et al. 2009; Van Wely et al. 2015). However, most herbicide treatments that included one PPO-inhibitor, excluding treatments not receiving a POST, controlled common ragweed similar to flumioxazin fb fomesafen. Herbicide treatments with similar common ragweed control 28 DA-POST to flumioxazin fb fomesafen included flumioxazin fb glufosinate and metribuzin, linuron, acetochlor, and clomazone all fb fomesafen. Furthermore, with the exception of Painter 2017, metribuzin fb glufosinate, linuron fb glufosinate, acetochlor fb glufosinate, and clomazone fb glufosinate, all programs lacking a PPO-inhibiting herbicide, provided comparable common ragweed control the two PPO-inhibiting herbicide system. Herbicide programs without a PPO-inhibiting herbicide did not control common ragweed as effectively as flumioxazin fb fomesafen 28 DA-POST at Painter 2017. This research demonstrates the excellent control by PPO-inhibiting herbicides for common ragweed control and why this herbicide mode of action needs to be preserved for the future.

Palmer Amaranth Control. Palmer amaranth control was evaluated at Painter Field 2 in 2018. With the exception of metribuzin and clomazone, residual herbicides provided excellent Palmer amaranth control 14 DA-PRE. Flumioxazin controlled Palmer amaranth 100% 14 DA-PRE (Table 32). Although linuron and acetochlor did not control common ragweed well, the herbicides controlled Palmer amaranth 99 to 100% 14 DA-PRE. At the same time, clomazone (84%) and metribuzin (81%) were less effective. At 28 DA-PRE, Palmer amaranth control by flumioxazin (100%), linuron (99%), and acetochlor (97%) remained excellent whereas control clomazone and metribuzin controlling Palmer amaranth no greater than 65%. Palmer amaranth densities were similar to visual estimates of control data. Seven days prior to POST, Palmer amaranth density in nontreated check plots averaged 96 plants m^{-2} (Table 33). Flumioxazin, linuron, and acetochlor reduced Palmer amaranth density 100, 98, and 97% relative to the nontreated check, respectively. Metribuzin and clomazone failed to reduce Palmer amaranth density greater than 43% compared to the nontreated check.

Later in the season, in the absence of a POST herbicide, flumioxazin controlled Palmer amaranth 100% 42, 56, and 70 DAP (Table 34). At the same rating intervals, linuron and acetochlor controlled the weed no less than 87 and 88%, respectively. Palmer amaranth control by metribuzin and clomazone in the absence of a POST herbicide continued to decline. Metribuzin and clomazone controlled Palmer amaranth 33% or less late in the season.

Previous research, as well as results from this experiment, confirms flumioxazin applied PRE provides excellent control of Palmer amaranth (Whitaker et al. 2010). Linuron and acetochlor control has also been previously noted (Sweat et al. 1998). Twenty-one days after PRE treatment, linuron and acetochlor controlled four *Amaranthus* species (including Palmer amaranth) almost completely (Sweat et al. 1998). Likewise, poor Palmer amaranth control by clomazone is well documented. (Scott et al. 2002). This experiment was conducted on a coarse-textured soil, which called for a lower rate of metribuzin (Anonymous 2009) and may explain poor Palmer amaranth control by metribuzin in this experiment. Other researchers have reported metribuzin at higher rates to provide excellent control of Palmer amaranth (Sweat et al. 1998).

Glufosinate and fomesafen applied POST greatly improved Palmer amaranth control in plots treated with a PRE herbicide. In the absence of a PRE herbicide where Palmer amaranth density was greater, glufosinate and fomesafen were less effective. Without a PRE herbicide, fomesafen controlled Palmer amaranth 48 and 51% 14 and 28 DA-POST, respectively (Table 34). Glufosinate was more effective in the absence of a PRE herbicide controlling Palmer amaranth 74% 14 DA-POST and 65% 28 DA-POST. However, when fomesafen and glufosinate were applied following a PRE herbicide, Palmer amaranth control averaged 94 to 97%.

Palmer amaranth density 14 DA-POST in nontreated plots averaged 141 plants m^{-2} (Table 35). Similar to control data, flumioxazin, linuron, and acetochlor, with no-POST, reduced Palmer amaranth density more than metribuzin or clomazone. Flumioxazin reduced Palmer amaranth density 100% and linuron and acetochlor both reduced density of the weed 96%

compared to the nontreated. Metribuzin and clomazone were not as effective, reducing Palmer amaranth density 58 and 25%, respectively.

Flumioxazin PRE fb fomesafen POST controlled Palmer amaranth excellent (100%) 14, 28, and 42 DA-POST. Additionally, Whitaker and others (2010) observed 93% Palmer amaranth control 90 days after POST herbicide application, when flumioxazin in combination with pendimethalin were applied PRE fb fomesafen POST. All treatments that contained just one PPO-inhibitor, with the exception of no PRE fb fomesafen, provided comparable Palmer amaranth control to flumioxazin fb fomesafen. Herbicide treatments including a PRE and POST but without a PPO-inhibitor, including metribuzin fb glufosinate, linuron fb glufosinate, and acetochlor fb glufosinate all controlled Palmer amaranth at least 82% 14 DA-POST and were also comparable to flumioxazin fb fomesafen. However, later in the season, Palmer amaranth control by clomazone fb glufosinate was not as effective as the two PPO-inhibiting herbicide system .

This research demonstrates that a residual herbicide applied PRE fb a timely POST herbicide control both common ragweed and Palmer amaranth well. Due to widespread glyphosate- and ALS-resistant common ragweed and Palmer amaranth reliance on PPO-inhibiting herbicides has increased (Sosnoskie and Culpepper 2014; Whitaker et al. 2011). While flumioxazin fb fomesafen did control both weeds well, other options must be adopted to reduce PPO selection pressure. Common ragweed and Palmer amaranth can be effectively controlled with several residual herbicides fb glufosinate or fomesafen applied POST. With the exception of flumioxazin fb glufosinate, PRE herbicides fb fomesafen POST controlled common ragweed better than a PRE herbicide fb glufosinate. Fomesafen applied POST appears to be a critical to controlling common ragweed, especially in non-glufosinate-resistant soybeans, where glufosinate POST is not an option. However, to reduce PPO selection pressure, it is essential to incorporate multiple effective MOA applied PRE. Alternatively, for soybean producers growing Liberty-Link soybean and wary of PPO resistance, it would be wise to use flumioxazin PRE fb glufosinate POST rather than fomesafen. Alternatives to flumioxazin applied PRE were also useful in limiting PPO-selection, especially for Palmer amaranth.

In conclusion, to effectively reduced PPO selection pressure, it would be wise to limit use of the herbicide mode of action to once per growing season. The use of a PPO-inhibiting herbicide in this experiment controlled both weeds well. This research demonstrates common ragweed and Palmer amaranth can be effectively controlled by herbicide programs limited to one PPO-inhibiting herbicide. Soybean producers must utilize many weed management practices to reduce the risk of herbicide development (Evans et al. 2015). Tank-mixing effective MOAs can reduce herbicide selection pressure in areas where herbicide resistance has yet to develop (Gressel et al. 2016). It would also be wise for soybean producers to use residual and POST combinations of two effective modes of action where appropriate.

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Tables

Table 24. Planting and herbicide application dates.

Location	**Year**	**Planting Date**	**Herbicide application date**	
			PRE	**POST**
Painter	2017	May 4	May 4	June 2
Suffolk	2017	May 17	May 17	June 14
Painter Field 1	2018	May 9	May 9	June 14
Painter Field 2	2018	May 9	May 9	June 7

Table 25. Herbicides and adjuvants used in experiments. [a]

Treatment	Trade Names	Application Rate Ha^{-1}	Formula Concentration	Manufacturer
flumioxazin	Valor ® SX	107 g ai	51%	Valent U.S.A. Corp.
metribuzin	TriCor 75 DF ®	262 g ai	75%	United Phosphorous, Inc.
linuron	Linex ® 4L	981 g ai	480 g ai L^{-1}	Tessenderlo Kerley, Inc.
acetochlor	Warrant ®	1262 g ai	360g ai L^{-1}	Monsanto Company
clomazone	Command ® 3ME	526 g ai	360g ai L^{-1}	FMC Corporation
fomesafen	Flexstar ®	423 g ai	225g ai L^{-1}	Syngenta Crop Protection, LLC
glufosinate	Liberty ® 280	656 g ai	280 g ai L^{-1}	Bayer CropScience
methylated seed oil[b]	MSO ® Concentrate with Leci-Tech	1% v v^{-1}	100 %	Loveland Products
ammonium sulfate[c]	Actamaster Soluble Crystal Spray Adjuvant	3363 g	100%	Loveland Products

[a] Product labels, mailing addresses, and web site addresses can be found at www.cdms.net.

[b] Methylated seed oil used with fomesafen.

[c] Ammonium sulfate used with glufosinate.

Table 26. Soybean injury 14 and 28 days after (DA) preemergence (PRE) herbicide treatments in Virginia. [a.b]

PRE [c]	**Soybean Injury** (%)	
	14 DA- PRE	28 DA-PRE
flumioxazin	11 a	6 b
metribuzin	0 a	3 c
linuron	0 a	10 a
acetochlor	0 a	3 c
clomazone	0 a	3 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

Table 27. Soybean response 14 and 28 days after (DA) postemergence (POST) herbicide treatments in Virginia. [a,b]

PRE [c]	**POST** [c,d]	**Soybean Injury** (%)	
		14 DA-POST	28 DA-POST
flumioxazin	fomesafen	18 b	6 ab
flumioxazin	glufosinate	6 ef	1 c
flumioxazin	nontreated	2 fg	0 c
metribuzin	fomesafen	17 bc	3 bc
metribuzin	glufosinate	3 fg	0 c
metribuzin	nontreated	0 g	0 c
linuron	fomesafen	25 a	8 a
linuron	glufosinate	5 fg	3 bc
linuron	nontreated	2 fg	3 bc
acetochlor	fomesafen	13 cd	3 bc
acetochlor	glufosinate	4 fg	0 c
acetochlor	nontreated	1 fg	0 c
clomazone	fomesafen	11 de	1 c
clomazone	glufosinate	1 fg	0 c
clomazone	nontreated	0 g	0 c
nontreated	fomesafen	17 bcd	3 bc
nontreated	glufosinate	3 fg	1 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 and 2 2018).

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

[d] PRE herbicides applied at planting. POST herbicides applied to 5-trifoliate soybean, 25 cm Palmer amaranth and 22 cm common ragweed.

Table 28. Common ragweed control 14 and 28 days after (DA) preemergence (PRE) herbicide treatments in Virginia.[a]

PRE [c]	**Common ragweed control** (%)	
	14 DA-PRE	28 DA-PRE
flumioxazin	98 a	91 a
metribuzin	49 c	52 c
linuron	73 b	80 b
acetochlor	46 c	45 c
clomazone	79 b	84 ab

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 2018).

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

Table 29. Common ragweed density prior to postemergence (POST) herbicide treatments in Virginia. [a,b]

PRE [c]	**Weed Density (plants m^{-2})**
	Common ragweed [d]
flumioxazin	3 c
metribuzin	64 b
linuron	19 c
acetochlor	118 a
clomazone	44 b
nontreated	114 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Common ragweed densities collected 20 days after soybean planting.

[b] Herbicide and adjuvant use rates in sources listed in Table 25.

[c] Data pooled across location (Painter 2017, Suffolk 2017, and Painter Field 1 2018).

Table 30. Common ragweed control by herbicide programs 14 and 28 days after (DA) postemergence (POST) herbicide treatments. [a]

PRE [b]	**POST** [b,c]	**Common ragweed control** (%)					
		14 DA-POST			28 DA-POST		
		Painter 2017	Suffolk 2017	Painter Field 1	Painter 2017	Suffolk 2017	Painter Field 1
flumioxazin	fomesafen	100 a	100 a	100 a	100 a	100 a	100 a
flumioxazin	glufosinate	99 a	98 a	100 a	90 ab	90 a	100 a
flumioxazin	nontreated	79 b	90 a	97 a	71 c	91 a	96 a
metribuzin	fomesafen	100 a	100 a	100 a	100 a	100 a	100 a
metribuzin	glufosinate	95 a	98 a	100 a	86 b	100 a	100 a
metribuzin	nontreated	0 d	53 b	33 d	0 e	45 b	29 c
linuron	fomesafen	100 a	100 a	100 a	100 a	100 a	100 a
linuron	glufosinate	100 a	100 a	100 a	86 b	99 a	100 a
linuron	nontreated	1 d	58 b	68 b	3 de	49 b	53 b
acetochlor	fomesafen	100 a	100 a	95 a	100 a	100 a	98 a
acetochlor	glufosinate	100 a	100 a	100 a	86 b	93 a	100 a
acetochlor	nontreated	3 d	3 d	0 e	0 e	5 c	3 d
clomazone	fomesafen	100 a	100 a	100 a	100 a	100 a	100 a
clomazone	glufosinate	99 a	100 a	100 a	88 b	100 a	100 a
clomazone	nontreated	25 c	28 c	49 c	11 d	29 b	40 bc
nontreated	fomesafen	100 a	100 a	98 a	100 a	100 a	100 a
nontreated	glufosinate	99 a	98 a	100 a	88 b	100 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide and adjuvant use rates in sources listed in Table 25.

[c] PRE herbicides applied at planting. POST herbicides applied to 5-trifoliate soybean and 22 cm common ragweed.

Table 31. Common ragweed density following postemergence (POST) herbicide treatments. [a]

PRE [c]	**POST** [c,d]	Weed density (plants m^{-2})		
		Common ragweed		
		Painter 2017	Suffolk 2017	Painter Field 1
flumioxazin	fomesafen	0 b	0 d	0 d
flumioxazin	glufosinate	0 b	0 d	1 d
flumioxazin	nontreated	18 b	0 d	3 d
metribuzin	fomesafen	0 b	0 d	0 d
metribuzin	glufosinate	6 b	0 d	1 d
metribuzin	nontreated	69 a	1 c	60 b
linuron	fomesafen	0 b	0 d	0 d
linuron	glufosinate	3 b	0 d	0 d
linuron	nontreated	56 a	1 c	11 d
acetochlor	fomesafen	1 b	0 d	2 d
acetochlor	glufosinate	1 b	0 d	0 d
acetochlor	nontreated	57 a	2 ab	96 a
clomazone	fomesafen	0 b	0 d	0 d
clomazone	glufosinate	0 b	0 d	0 d
clomazone	nontreated	58 a	1 bc	34 c
nontreated	fomesafen	0 b	0 d	1 d
nontreated	glufosinate	3 b	0 d	0 d
nontreated		65 a	2 a	68 b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Common ragweed densities collected 14 days after POST application.

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

[d] PRE herbicides applied at planting. POST herbicides applied to 5-trifoliate soybean and 22 cm common ragweed.

Table 32. Palmer amaranth control 14 and 28 days after (DA) preemergence (PRE) herbicide treatments at Painter Field 2 2018. [a]

PRE [b]	**Palmer amaranth control** (%)	
	14 DA- PRE	28 DA-PRE
flumioxazin	100 a	100 a
metribuzin	81 b	65 c
linuron	100 a	99 ab
acetochlor	99 a	97 b
clomazone	84 b	63 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide and adjuvant use rates in sources listed in Table 25.

Table 33. Palmer amaranth density prior to postemergence (POST) herbicide treatments at Painter Field 2 2018. [a,b]

PRE [c]	**Weed Density (plants m^{-2})**
	Palmer amaranth
flumioxazin	0 c
metribuzin	58 b
linuron	2 c
acetochlor	3 c
clomazone	55 b
nontreated	96 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Palmer amaranth densities collected 20 days after soybean planting.

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

Table 34. Palmer amaranth control by herbicide programs 14, 28, and 42 days after (DA) postemergence (POST) herbicide treatments at Painter Field 2 2018. [a]

PRE [b]	**POST** [b,c]	**Palmer amaranth control** (%)		
		14 DA-POST	28 DA-POST	42 DA-POST
flumioxazin	fomesafen	100 a	100 a	100 a
flumioxazin	glufosinate	100 a	100 a	100 a
flumioxazin	nontreated	100 a	100 a	100 a
metribuzin	fomesafen	90 ab	94 ab	100 a
metribuzin	glufosinate	93 ab	84 abc	92 ab
metribuzin	nontreated	13 d	33 e	13 e
linuron	fomesafen	100 a	100 a	100 a
linuron	glufosinate	96 a	96 ab	93 ab
linuron	nontreated	87 ab	88 ab	90 ab
acetochlor	fomesafen	100 a	100 a	100 a
acetochlor	glufosinate	99 a	99 a	100 a
acetochlor	nontreated	89 ab	89 ab	88 ab
clomazone	fomesafen	93 ab	91 ab	85 ab
clomazone	glufosinate	82 ab	76 bc	81 bc
clomazone	nontreated	30 cd	10 f	3 e
nontreated	fomesafen	48 c	51 de	49 d
nontreated	glufosinate	74 b	65 cd	69 c

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Herbicide and adjuvant use rates in sources listed in Table 25.

[c] PRE herbicides applied at planting. POST herbicides applied to 5-trifoliate soybean and 25 cm Palmer amaranth.

Table 35. Palmer amaranth density following postemergence (POST) herbicide treatments at Painter Field 2 2018. [a]

PRE [c]	**POST** [c,d]	Weed density (plants m^{-2})
		Palmer amaranth
flumioxazin	fomesafen	0 e
flumioxazin	glufosinate	1 e
flumioxazin	nontreated	0 e
metribuzin	fomesafen	10 e
metribuzin	glufosinate	25 de
metribuzin	nontreated	59 cde
linuron	fomesafen	0 e
linuron	glufosinate	11 e
linuron	nontreated	5 e
acetochlor	fomesafen	0 e
acetochlor	glufosinate	1 e
acetochlor	nontreated	5 e
clomazone	fomesafen	21 de
clomazone	glufosinate	33 de
clomazone	nontreated	106 abc
nontreated	fomesafen	155 a
nontreated	glufosinate	82 bcd
nontreated		141 ab

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Palmer amaranth densities collected 14 days after POST application.

[c] Herbicide and adjuvant use rates in sources listed in Table 25.

[d] PRE herbicides applied at planting. POST herbicides applied to 5-trifoliate soybean and 25 cm Palmer amaranth.