The Evaluation of HPPD-Inhibitors for Full-Season Control of Morningglory (*Ipomoea)* Species in Corn (*Zea mays* L.)

by

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Abstract

Due to late-season morningglory harvest interference concerns in corn, field studies were conducted in 2017 and 2018 at the Prattville Agricultural Research Unit in Prattville, Alabama and at the Sand Mountain Research and Extension Center in Crossville, Alabama to evaluate late season control of morningglory species using HPPD-inhibitors postemergence (POST) applied alone, following atrazine preemergence (PRE), or in combination with atrazine. Additionally, *Amaranthus* spp. and *Senna* spp. were evaluated for control. An incomplete randomized design with a split-plot treatment arrangement with four replications was utilized. The trial was divided into two sections: one with a PRE application of atrazine and a second without a preemergence application of atrazine. Eleven herbicides were applied POST without atrazine including: tembotrione; mesotrione; topramezone+dimethenamid; mesotrione+S-metolachlor+glyphosate; tembotrione+thiencarbazone; topramezone; mesotrione+S-metolachlor+atrazine; mesotrione+S-metolachlor+atrazine+bicyclopyrone; mesotrione+nicosulfuron; isoxaflutole; isoxaflutole+thiencarbazone-methyl; non-treated with atrazine applied PRE, and a true non-treated check. The same herbicides, excluding the two treatments that contain atrazine in the premixture, were also applied with atrazine. Herbicide treatments were applied at the V3-V4 stage of corn or a maximum crop height of 30 cm (12 in.) in height. Visual control ratings of *Ipomoea* spp., primarily *Ipomoea hederacea* (ivyleaf morningglory), *Ipomoea herderacea* var. *integriuscula* (entireleaf morningglory), and *Ipomoea lacunosa*, (pitted morningglory), *Senna* spp., and *Amaranthus* spp., were recorded at 30, 60, 90 days after treatment (DAT), and at harvest. Yield was also evaluated. Control was evaluated on a visual scale of 0-100% with 0 = no control and 100% = total control. The 30, 60, and 90 DAT morningglory control ratings did not have a significant atrazine or treatment ∗ atrazine effect. Significant herbicide treatment effects were analyzed for these time intervals. Most HPPD-inhibitor treatments ranged from 89% to 98%. Topramezone decreased from 93% morningglory control 30 DAT to 83% 90 DAT. Tembotrione decreased in efficacy from 95% to 83% across the same timeframe. Only the at-harvest morningglory control rating had a significant atrazine or treatment * atrazine effect. With atrazine, control ranged from 75% to 93% across treatments, while HPPD inhibitor treatments applied without atrazine ranged from 65% to 94%. The lowest morningglory control at harvest followed topramezone applied without atrazine at 65% control and tembotrione without atrazine at 70% control, the only HPPD-inhibitors with significant differences from most of the remaining treatments. *Amaranthus* spp. control was excellent as control ranged from 95% to 99% from 30 DAT to harvest across all HPPD-inhibitor treatments. *Senna* spp. control generally declined as the season progressed. At 30 DAT, control ranged from 90% to 95%. At harvest, control ranged from 61% to 81%, though there were no statistical differences between HPPD-inhibitor treatments. The treatment of S-metolachlor plus atrazine plus mesotrione had the least drastic numerical drop in *Senna* spp. control with 95% control at 30 DAT to 81% rating at harvest. There were no differences in corn yield between HPPD-inhibitor treatments. The results of this trial may suggest that there is no difference if HPPD-inhibitor treatments are applied POST alone in corn, after an atrazine PRE application, versus the addition of atrazine in the POST treatment, as the combination had little significant effect on weed control, with the exception of topramezone and tembotrione control of morningglory control at harvest. This comprehensive side-by-side comparison, of some of the most common commercially available HPPD-inhibitor herbicides for corn in the US, could potentially provide producers with more information for full season corn weed control in Alabama.

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Table of Contents

List of Tables

I. The Evaluation of HPPD-Inhibitors for Postemergence Control of Late Season Morningglory (*Ipomoea)* Species in Corn (*Zea mays* L.)……………………………….1

The Evaluation of HPPD-Inhibitors for Full-Season Control of Morningglory (*Ipomoea)* Species in Corn (*Zea mays* L.)

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Several HPPD (4-phenylhydroxypyruvate dioxygenase) products are currently available in corn including standalone HPPD products and products with multiple mechanisms of action (MOA). Some of these are combination products but have a common HPPD-inhibitor MOA to control broadleaf and grass weeds, yet none have been evaluated in a comprehensive side-by-side comparison to evaluate the differences between these products. Morningglories (*Ipomoea* spp.) have traditionally been a difficult weed to control full season in corn making it problematic at harvest time. The objectives of this study were to determine the efficacy of HPPD-inhibitor products, with atrazine POST, or following atrazine PRE, and evaluate the differences for full-season morningglory control, particularly late season control. Additionally, we evaluated other broadleaf species that emerge in the field (*Amaranthus* spp. and *Senna* spp.) to determine which product(s) works best on each species. Traditionally, atrazine is added a preemergence treatment and an early-postemergence treatment to corn due to high efficacy and it's low cost, though the atrazine PRE (1.12 kg ai ha^{-1}) only treatment in this trial resulted in poor control. Morningglory control across all HPPD-inhibitor treatments was above 83% at 90 DAT. At harvest, control

ranged from 75% to 94% across treatments applied POST with and without atrazine, with the exception of topramezone that resulted in 85% control with atrazine and 65% without atrazine at harvest. Additionally, tembotrione provided 75% and 70% control with and without atrazine, respectively. *Amaranthus* spp. were effectively suppressed until harvest with all HPPD-inhibitor treatments, with the exception of atrazine PRE alone that ranged from 74% 30 DAT to 60% control at harvest. A general decrease in control of *Senna* spp. was observed from 30 DAT to harvest, yet no treatments were statistically different. No statistical yield differences were recorded between HPPD-inhibitor treatments, as compared to the non-treated check.

Introduction

The History of HPPD Inhibiting Herbicides

The 4-phenylhydroxypyruvate dioxygenase (HPPD) enzyme is the newest site of action (SOA) exploited for herbicidal action (Duke 2012). The HPPD inhibiting herbicides are classified into the triketones, pyrazoles, and isoxazoles (Lee et. 1997; van Almsick 2009). The triketones are comprised of the herbicidal compounds mesotrione, tembotrione, sulcotrione, and bicyclopyrone (Strachan 2013). These triketones have a chemical structure designed around the benzoylcyclohexanedione molecule (Beaudegnies et al. 2009). The main symptomology of the triketones is “potent bleaching” with different properties than previously available classic bleaching herbicides which primarily affect phytoene desaturase (PDS) directly (Lee et al. 1997). Two separate events led to the discovery of the eventual herbicidal triketone class. In 1977, a scientist at Western Research Center, CA for Zeneca Ag Products noticed fewer plants grew under a bottle brush plant (*Callistemon citrinus*) (Lee et al. 1997). Compounds were isolated from the bottle brush plant and structural analysis determined the active compound to be leptospermone, which was previously reported by (Hellyer 1968) as being a component of steam-volatile oils in Australian myrtaceous plants. Testing of leptospermone showed moderately effective control on a few weed species in conjunction with unique bleaching effects at a rate of 1000 g ha^{-1} or more (Gray et al. 1980). Leptospermone herbicidal activity and synthetic analogues of leptospermone, known as alkanoyl syncarpic acids, were patented in 1980 (Gray et al. 1980). Additionally, in 1982, a second event led to the herbicidal triketone class discovery. Scientists at the same Western Research Center were experimenting with the creation of novel acetylcoenzyme-A carboxylase (ACCase) compounds to replicate the herbicide sethoxydim (Lee at al. 1998; Michaely and Kratz 1986). A herbicidally inactive benzoylcyclohexanedione compound was created, instead of the expected analog, yet further studies being performed for soybean injury antidotes showed promise for the compound to be a possible antidote (Lee et al. 1998). A 2-chlorobenzoyl analog was created, as a result of the program to find further analog antidotes, and was found to be herbicidally active with the same bleaching effects of leptospermone (Lee et al. 1998). The removal of methyl groups and addition of a chlorine group to the cyclohexanedione structure produced a significantly enhanced herbicidal compound and the discovery of the herbicidal triketones (Lee et al. 1998).

The benzoylisoxazole, or isoxazole class, family of HPPD inhibitors includes the chemical isoxaflutole which can be used as a PRE or POST herbicide for selective grass and broadleaf weed control in corn (Luscombe and Pallet 1996; Pallet et al. 98; Pallet et al. 2001). They are included in the larger ‘diketone’ class of herbicides that includes the benzoylcyclohexanediones and the benzoylpyrazoles (Lee et al. 1997; Luscombe et al. 1995; Pallett et al. 2001). In 1984, attempts by scientists at the Dagenham Research Centre to discover new hydroxymethylglutaryl coenzyme A reductase inhibitors, led to the discovery of a weakly herbicidally active compound named M&B 43087. Further work showed it had a similar structure to the graminicide (grass herbicide) sethoxydim. Eventually, a further refined compound named M&B 46206 showed PRE and POST control of some broadleaf and grass species at 62 g ai ha^{-1} with similar bleaching symptomology in susceptible species. Research briefly stopped due to patent issues, but was re-started and in 1989, research led to the discovery of the synthesis of the first benzoyl isoxazole named RPA 200809. This compound was herbicidally active and showed some broadleaf weed control applied PRE at 250 g ai ha^{-1}, but further refining by the replacement of a methyl group with a cyclopropyl group enhanced the grass weed activity of the compound (now RPA 201 096). Lastly, the compound was refined again by adding a sulfur dioxide group in place of a nitrogen dioxide group to create RPA 201 772. This compound showed excellent broad spectrum control of main US corn weeds applied PRE at 62 g ai ha^{-1} and was subsequently name isoxaflutole (Luscombe and Pallet 1996; Pallet et al. 98; Pallet et al. 2001).

The benzoylpyrazole, or pyrazolone, class of herbicides includes the compound topramezone which was first introduced commercially in 2006 for wide spectrum control of annual grasses and broadleaf weeds in corn (Grossman and Ehrhardt 2007; Siddal et al. 2002; Schönhamer et al. 2006). The benzoylpyrazole area of chemistry was discovered by Sankyo Co. Ltd. researchers (Yasu, Shiga (Japan)) and subsequently they commercially introduced the compounds pyrazoxyfen and pyrazolate in 1984 and 1986, respectively, for use in rice (Kimura 1984; Yamaoka et al. 1988; Kawakubo et al. 1979). The benzoylpyrazoles are a part of a larger class of herbicides classified as 'diketone' herbicides that includes the benzoylcyclohexanediones and benzoylisoxazoles (Lee et al. 1997; Luscombe et al. 1995; Pallett et al. 2001). This class of herbicides was expanded when additions to the benzene ring of the compounds produced favorable attributes, such as necrosis and plant death, with activity on both grasses and broadleaf weeds. Additional favorable attributes included preemergent and postemergent activity and selectivity in some major crops for this relatively new mode of action (Benko et al. 1998).

The Mode of Action of HPPD-Inhibiting Herbicides

As previously mentioned, the 1982 discovery of the triketone class of herbicides led to speculation of the mode of action of these herbicides (Lee et al. 1997). The broad spectrum class of herbicides, noted for their PRE and POST activity, were introduced for broadleaf weeds and grass control in corn due to the crop's tolerance of the herbicides. Prominent bleaching symptomology was reported from this class of herbicides with bleaching symptoms appearing on meristematic tissue first, with an increase in levels of phytoene *in vivo* (Lee et al. 1997; Mayanado et al. 1989; Soeda and Uchida 1987). However, phytoene desaturase *in vitro* was reported to not be inhibited by the triketones (Sandman et al. 1990). While looking for possible explanations for the bleaching symptomology, tyrosine hydroxylase inhibitors were next expected to be the possible mode of action for the triketones (Gray 1980; Lee et al. 1997; Lee 1984). A study was conducted to determine how tyrosine levels were affected in rats when treated with the triketone herbicide NTBC due to the speculation that this was the mode of action of the triketones (Lee et al. 1997). NTBC treated rats were treated with a high and low dosage and compared to untreated control rats with the testing technique of colorimetric assays. The two arrays used were a ferric chloride assay and nitrosonaphthol assay, which detect p-hydroxyphenylpyruvate and p-hydroxyphenyl compounds, respectively (Lee et al. 1997; Tietz 1986a; Tietz 1986b). The urine from the triketone treated rats tested positive in both assays (Lee et al. 1997). Ellis et al. (1995) tested for elevated levels of plasma tyrosine concentrations, in the treated rats, via HPLC and found elevated levels of tyrosine in both high and low NTBC dosed rats as compared to the untreated. Therefore, tyrosine hydroxylase was found to not be inhibited by the triketone NTBC (Ellis et al.

1995). Further tests were conducted by Ellis et al. (1995) and nuclear magnetic resonance analysis of the urine from the NTBC treated rats revealed large amounts of p-hydroxyphenylpyruvic and p-hydroxyphenyllactic acids. This finding led to the speculation that NTBC might affect an enzyme in tyrosine metabolism with one of the compounds as a substrate. The substrate p-Hydroxyphenylpyruvate was found to belong to the HPPD enzyme and that NTBC, and other triketones, were potent in the inhibition of HPPD isolated from rat livers (Lindsted and Odelhög 1987; Ellis et al. 1995). Identifying HPPD as the target site in triketone treated rats was a breakthrough in discovering the mode of action of the triketone herbicides, but only completed the first step. Next, the focus was to confirm that the HPPD enzyme was the target site for plants using the triketone herbicides.

Methods to discover the target site of HPPD inhibitors in plants had to evolve before confirmation. Schultz et al. (1985) had already found that the HPPD enzyme was a part of the biosynthetic pathway that leads to the production of the important compounds plastoquinone and tocopherols (and subsequently carotenoids). Plastoquinone, a critical cofactor of phytoene desaturase, was found to be the leading cause of bleaching symptoms when depleted, causing a reduction of carotenoids (Mayer et al. 1990; Mayer et al. 1992; Norris 1995). Eventually, Prisbylla et al. (1993) found a large accumulation of tyrosine and a depletion of plastoquinone in ivyleaf morningglory (*Ipomoea hederacea)* treated with the triketones NTBC and sulcotrione. Subsequently, plant HPPD was found to be inhibited by the triketones through analysis of their combination of effects on plants (Prisbylla et al. 1993; Secor 1994; Schultz et al. 1993). Later, Matsumoto (2005) confirmed the HPPD enzyme as the target site in the pyrazolone class of herbicides and Viviani et al. (1998) confirmed the target site in the isoxazole class of herbicides.

The complete mode of action of these bleaching herbicides is easier to comprehend now that the target site has been established as the HPPD enzyme. Schultz et al. (1985) reported that homogentisic acid produces plastoquinones and tocopherols during the breakdown of tyrosine, with this acid also being synthesized by HPPD and HPPA. Studies have shown that the addition of homogentisic acid to plants treated with triketone herbicides prevented injury to the plants (Prisbylla et al. 1993; Schultz et al. 1993). As previously mentioned, plastoquinones are critical cofactors in phytoene conversion by phytoene desaturase in carotenoid synthesis (Mayer et al. 1990; Mayer et al. 1992; Norris et al. 1995). Pallett et al. (1998), when reporting on isoxaflutole activity in plants, discovered a decrease in plastoquinones, tocopherols, and carotenoids when homogentisic acid is depleted due to the inhibition of the HPPD enzyme. Loss of plastoquinones inhibits the production of carotenoids leaving the plant without the ability to defend itself against photoxidation. Photoxidation then occurs from the inability to quench triplet chlorophyll and destructive singlet oxygen is formed (Siefermann-Harms 1983). Additionally, the inability to produce carotenoids to fight against photoxidation leads to membrane along with pigment destruction, and ultimately bleaching symptomology. Kaiser et al. (1990) discovered that tocopherols have the ability to physically quench destructive singlet oxygen giving rise to the assumption that they can prevent photoxidation. Though they can prevent photoxidation to a minor capacity, Havaux et al. (2005) reported that only under extreme conditions (extreme cold and high light intensity) that plants missing tocopherols succumbed to photoxidation with carotenoids being suggested as an aid in prevention and protection in a normal plant environment. Thus, the collective research proposes that the HPPD inhibitor mode of action is the depletion of carotenoids, due to a loss of plastoquinones from the inhibition of the HPPD enzyme, and subsequent photoxidation leading to bleaching and membrane destruction.

Herbicidal Efficacy and Characteristics of HPPD-Inhibiting Herbicides

The broad spectrum activity against broadleaf weeds and grasses has made the use of HPPD inhibitors more prevalent in crops that are more tolerant to the herbicides such as corn, wheat (*Triticum aestivum* L.), and rice (*Oryza sativa* L.). These potent bleaching herbicides provide producers the option to include this relatively newer mode of action into treatment regimens to fight against potential resistance issues and utilize more environmentally friendly herbicides than previously. For the 2016 crop year, 97% of planted corn acres had herbicides applied while 60% of the planted acres had atrazine applied (USDA/NASS 2018). Additionally, 57% of total treated corn acres were treated with either mesotrione (28%), isoxaflutole (12%), tembotrione (7%), topramezone (6%), or bicyclopyrone (4%) (USDA/NASS 2018). HPPD inhibiting herbicides were first introduced the southern United States (Alabama, Florida, Georgia, Kentucky, North Carolina, South Carolina, and Tennessee) in 2001, with 9% of the corn area receiving an application, which increased to 26% in 2005 (Webster and Nichols 2012). The compounds utilized represent the triketone class (mesotrione, tembotrione, and bicylcopyrone), isoxazole class (isoxaflutole), and pyrazolone (topramezone) class of herbicides that are defined as HPPD inhibitors and are the predominantly used HPPD inhibiting herbicides for weed control in corn in the United States.

Triketone class

The commercially available triketone herbicides, for use in corn, are mesotrione, sulcotrione, tembotrione, and bicyclopyrone. Mesotrione, a product of Syngenta, applied PRE at rates of 100 to 225 g ha^{-1} and 70 to 150 g ha^{-1}, is an effective broad spectrum broadleaf and grass herbicide that is taken up rapidly by weed species and is translocated both acropetally (upwards from the roots to the shoots) and basipetally (downwards from the foliage towards the roots) (Mitchell et al. 2001). Bleaching symptomology to plant necrosis is observed within 3-5 DAT (Shaner 2014). Broadleaf weeds susceptible to mesotrione include rough cocklebur (*Xanthium strumarium L.*), velvetleaf (*Abutilon theophrasti Medik.*), giant ragweed (*Ambrosia trifida L.*), and *Chenopodium* (lambsquarters), *Amaranthus* (pigweed), and *Polygynum* (knotweed) species (Mitchell et al. 2001; Wichert et al. 1999; Reddy and Bhowmik). Additionally, mesotrione can control *Digitaria* and *Echinochloa* grass species (Wichert et al. 1999). Armel et al. (2003) demonstrated POST treatments of mesotrione following PRE treatments of mesotrione, atrazine, or acetochlor provided at least 87% control of *Ipomoea spp.* (morningglory) species 8 weeks after treatment (WAT). Mesotrione applied POST alone has shown to provide at least 89% control 4 weeks after emergence (4 WAE) in both pitted (*Ipomoea lacunosa L.*) and entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula*) (Stephenson IV et al. 2004). Studies have demonstrated inconsistent morningglory control with mesotrione alone, but morningglory species (ivyleaf (*Ipomoea hederacea Jacq.*), pitted, and tall morningglory (*Ipomoea purpurea (L.) Roth*)) treated with mixtures of mesotrione, S-metolachlor, and atrazine PRE were controlled at least 90% 6 WAT (Whaley et al. 2009). There is inconsistent data on season long control.

Sulcotrione, the first commercially available benzoylcyclohexandione was registered in Europe for corn production in 1993 (Beaudegenies et al. 2009). Typical use rates for sulcotrione are .25 – 1 kg ha^{-1} applied PRE and POST at the 5 – 6 leaf development stage in corn (Beraud et al. 1991; Wilson and Foy 1990; Prisbylla et al. 1993; Cherrier et al. 2005). Sulcotrione can control certain annual broadleaf and grass weeds. Grass weeds controlled include large crabgrass (*Digitaria sanguinalis (L.) Scop.*), barnyardgrass (*Echinochloa crus-galli (L.) P. Beauv.*), fall panicum (*Panicum dichotomiflorum Michx.*), foxtails (*Setaria spp.*), and *Festuca* species (Beraud et al. 1991). Broadleaf weeds controlled include common lambsquarters (*Chenopodium album L.*) and *Amaranthus spp.* (Beraud et al. 1991).

Tembotrione is effective against a wide range of broadleaf and grass weed species at recommended rates of 75 to 100 g ha^{-1} applied POST (van Almsick et al 2009; Hinz et al. 2005). Whitening of the apical meristem followed by necrosis and plant death is observed within a few days after application (Shaner 2014). Tembotrione is particularly more effective than some other HPPD inhibitors for the control of foxtails and wooly cupgrass (*Eriochloa villosa (Thunb.) Kunth*) and can be a useful tool for fighting ALS- and glyphosate-resistant weeds (van Almsick et al. 2009). Additionally, residual efficacy of tembotrione has been observed with levels of weed control declining in heavier soils higher in organic matter as compared to lighter soils, at a low rate of 12.5 g ai ha^{-1}, and control up to 2-4 weeks with high light intensity (Gatzweiler et al. 2012). Weeds species controlled by tembotrione include *Amaranthus* species, common lambsquarters, common ragweed (*Ambrosia artemisiifolia L.*), velvetleaf, giant foxtail (*Setaria faberi Herrm.*), and barnyardgrass (Lamore et al. 2006; Simkins et al. 2006; Zollinger and Ries 2005). Tembotrione can cause injury to some corn varieties applied alone, but the herbicide is commercially available as a premix with the safener isoxadifen-ethyl which allows for more effective crop metabolism and high crop tolerance in corn as a POST herbicide (Ahrens et al. 2013; van Almsick 2009; Hinz et al. 2005; Hora et al. 2005; Gatzweiler et al. 2012). Safeners reduce the amount of crop injury through physiological or molecular mechanisms by allowing higher herbicide rates to be used, thus reducing the amount of escaped weeds when compared to using lower rates with more crop safety (Hoffman 1962; Hatzios and Burgos 2004). In corn, ~82% of tembotrione was metabolized 24 hours after treatment (Schulte and Köcher 2009)   Tembotrione has shown effectiveness for the control of large crabgrass, entireleaf morningglory, ivyleaf morningglory, browntop millet (*Urochloa ramosa (L.) Nguyen*), Pennsylvania smartweed (*Persicaria pensylvanica (L.)*), prickly sida (*Sida spinosa L.*), and yellow foxtail (*Setaria pumila (Poir.) Roem. & Schult.*) (Stephenson IV et al. 2015; Bararpour et al. 2011; Loux et al. 2008). Loux et al. 2008 reported ≥90% control of ivyleaf morningglory (tembotrione applied POST with the addition of atrazine) and velvetleaf (tembotrione applied POST) at season's end, but many studies have not reported on season long morningglory control.

Lastly, the triketone herbicide bicyclopyrone is the newest HPPD inhibitor for commercial use in corn. Bicyclopyrone is available premixed with atrazine, mesotrione, and S-metolachlor and is a product of Syngenta. The premix has been commercialized for pre-plant, PRE, and POST control of broadleaf and annual grass weeds in corn (Anonymous 2015). The combination of multiple MOAs is suspected to help control resistant and problematic weeds in corn. Bicyclopyrone, applied PRE at 0.48 kg ha^{-1}, provided 92% or greater residual control 86 DAT of common lambsquarters, common purslane (*Portulaca oleracea L.*), redroot pigweed (*Amaranthus retroflexus L.*), common ragweed, and yellow foxtail (Colquhoun et al. 2016). Additionally, the premix has proven to control Asiatic dayflower (*Commelina communis L.*) and barnyardgrass (Grichar et al. 2017). When applied PRE and post-directed at 37.5 and 50g ha^{-1}, multiple vegetable species showed tolerance when grown in high organic matter soil (Chen et al. 2018). Several glyphosate-resistant species such as Palmer amaranth (*Amaranthus palmeri S. Watson*), horseweed (*Erigeron canadensis L.*), and Russian thistle (*Salsola kali L.*) have shown to be effectively controlled by products containing bicyclopyrone (Janak and Grichar 2016; Kumar et al. 2017; Sarangi and Jhala 2017).

Isoxazole class

Isoxaflutole belongs to the isoxazole class of HPPD-inhibiting herbicides and can be applied PRE to early POST in sugarcane and corn (Cain et al. 1993; Bhowmik et al. 1996; Luscombe et al. 1995; Luscombe and Pallet 1996). It is a novel herbicide for broadleaf and grass weed control when applied at rates of 75 to 140 g ai ha^{-1}, with primary absorption and translocation within the xylem (Bhowmik et al. 1996; Luscombe et al. 1995; Shaner 2014). Broadleaves susceptible to isoxaflutole include velvetleaf, common ragweed, common lambsquarters, *Amaranthus* spp., and common ragweed (Luscombe and Pallet 1996; Shaner 2014). Grasses susceptible include fall panicum, wild proso millet (*Panicum miliaceum L.*), barnyardgrass, and foxtails (Luscombe and Pallet 1996; Shaner 2014). A safener, cyprosulfamide, is included in the mix with isoxaflutole to provide crop protection as isoxaflutole alone can cause injury when applied both PRE and early POST (Ahrens et al. 2013). The premixture of isoxaflutole and thiencarbazone-methyl, an ALS inhibitor produced by Bayer, also has cyprosulfamide included in the mixture and adds an additional MOA (Ahrens et al. 2013). The actual isoxaflutole compound is not the principle compound that induces injury within susceptible species. Rather, through foliar or root uptake, opening of the isoxazole ring in the compound causes a rapid conversion to a diketonitrile derivative within the plant (Pallet et al. 1998). The extent of degradation within the plant correlates how susceptible the plant is to injury. Studies reported a slower rate of degradation in susceptible velvetleaf and the most rapid degradation in tolerant corn (Pallet et al. 1998). C^{14} extracted from corn and velvetleaf, following a PRE application of a high rate isoxaflutole equivalent to 250 g ai ha^{-1}, produced a result of only 10% diketonitrile derivative left in tolerant corn as compared to 90% left in susceptible velvetleaf (Pallet et al. 1998). Additionally, the rate of degradation in *Ipomoea* spp. was reported as being intermediate, labeling them as moderately susceptible to isoxaflutole (Pallet et al. 1998).

Pyrazolone class

Topramezone is a highly selective, postemergence herbicide belonging to the pyrazolone class of HPPD-inhibiting herbicides. It was introduced in 2006 by BASF Corporation at a postemergence application rate range of 12-25 g ai ha^{-1} for annual broadleaf and grass weed control in corn (Grossman and Ehrhardt 2007; Porter et al. 2005; Schönhammer et al. 2006; Soltani et al. 2007). Crop selectivity allows for this herbicide to be applied in the 1- to 8-leaf stage of corn (Schönhammer et al. 2006). Through acropetal and basipetal movement within the plants, topramezone has shown to control early and late germinating dicotyledenous species such as common lambsquarters, *Atriplex* (orache), *Amaranthus* spp., *Solanum* spp., and *Galinsoga* (quickweed species) through ready absorption in the roots and shoots (Schönhammer et al. 2006; Grossman and Ehrhardt 2007; Zollinger and Ries 2006; Goršić et al. 2008). Additionally, topramezone has been reported to control warm season annual grasses such as barnyardgrass, foxtails, crabgrasss, and panicum species (Schönhammer et al. 2006). Tank mixing an adjuvant, such as methylated seed oil (MSO), has shown to improve absorption of topramezone in giant foxtail and velvetleaf 68.9% and 45.9%, respectively (Zhang et al. 2013). The selectivity of topramezone between corn and other species has been reported as above 1000-fold, with corn having more rapid metabolism and lower sensitivity to the HPPD enzyme (Schönhammer et al. 2006; Grossman and Ehrhardt 2007). Multiple studies have reported no differential sensitivity and minimal injury amongst sweet corn hybrids and field corn treated with high rates of topramezone (Soltani et al. 2007; Bollman et al. 2008; Gistopolous 2010).

Combining HPPD inhibitors and photosystem II (PSII) inhibitors, mostly atrazine, has been thought of as a synergistic accompaniment since the release of mesotrione. A disruption of carotenoid synthesis, via HPPD inhibitors, through plastoquinone inhibition and tocopherol synthesis leads to a disruption of the D1 protein within photosystem II, of which PSII inhibitors compete with plastoquinones to occupy (Norris et al. 1995; Hess 2000; Trebst et al. 2002). The increase in plastoquinones, due to the PSII inhibitor controlling the protein site, causes a blockage of electron flow from photosystem II to photosystem I. This leads to an accumulation of singlet chlorophyll, triplet chlorophyll, and singlet oxygen, which in turn causes membrane destruction (Hess 2000). The combination of HPPD inhibitors and PSII inhibitors is suspected to be synergistic due to an absence of plastoquinone at the D1 protein by the HPPD inhibitor, allowing the PSII inhibitor to more effectively control the protein and block electron transfer (Armel et al. 2005; Abendroth 2006). The triplet chlorophyll and singlet oxygen accumulation due to PSII inhibition, plus the loss of tocopherols and carotenoids by HPPD inhibition could lead to synergy between the two different MOAs (Creech et al. 2004). Many studies have reported synergistic weed control tank-mixing atrazine and HPPD inhibitors in broadleaf and grass species (Armel et al; Armel et al. 2003; Armel et al. 2005; Johnson et al. 2002; Hugie et al. 2008; Sutton et al. 2002; Williams et al. 2011). Creech et al. (2004) reported consistent reduction in dry mass and photosynthesis when using both mesotrione and atrazine, stating that using a combination of the herbicides is more effective than either herbicide alone.

***Ipomoea* spp. Biology**

In a study from 2007 to 2013, corn was determined to be grown on more than 90 million acres in North America, worth an estimated $52 billion when using Best Management Practices (Soltani et al. 2016). Without the use of herbicidal weed control, an average of 52% crop (148 million tonnes) loss would occur, costing approximately $26.7 billion annually (Soltani et al. 2016). In a survey amongst Weed Science Society of America Members, *Ipomoea* spp. ranked fourth for most common and third for most troublesome weeds in corn (Van Wychen 2017). From 1994 to 2008, a study of the most troublesome weeds in corn in the southern United States (Alabama, Florida, Georgia, Kentucky, North Carolina, South Carolina, and Tennessee) ranked *Ipomoea* spp. from fourth to first, from 1994 to 2008, respectively (Webster and Nichols 2012).

Pitted, ivyleaf, and entireleaf morningglory species belong to the Convolvulaceae family and are included within the *Ipomoea* genus, of which there are 500-700 species throughout the world (Austin and Huáman 1996; Mabberley 1989; McDonald and Mabry 1992). Morningglory species are very prevalent throughout agricultural production systems in the southeastern United States (SWSS 2012). *Ipomoea* species are labeled as herbaceous, viney, summer annuals, which have climbing and creeping habits (Elmore et al. 1990). This family is characterized by its vining ability which can cause corn to lodge, cause crop yield loss, and reduce harvest efficiency (Crowley and Buchanan 1978; Howe and Oliver 1987; Radosevich et al. 2007). Crop yield loss can also be due to the species' ability to compete for light, water, and nutrients (Cordes and Bauman 1984; Howe and Oliver 1987; Holloway and Shaw 1996). Morningglory species prove difficult to control as they are moderately tolerant to glyphosate. Reduced efficacy of glyphosate can contribute to re-establishment of populations after application timing, and improper control can lead to population increases (Marshall et al. 2002; Hilgenfield et al. 2004; Radosevich et al. 2007).

Pitted morningglory has been characterized as a sparsely pubescent, twining annual with ovate, entire, or arrow shaped leaves that range from 8 to 45 cm^2, and have a white funnel-shaped flower (Radford et al. 2010). Plants have been observed to produce from 10,000 to 15,000 seeds per $plant^{-1}$ or 52.3 million seed per ha^{-1} when untreated (Chandler et al. 1978; Crowley and Buchanan 1982; Norsworthy and Oliver 2002). Egley and Chandler (1983) state the hard seed coat of pitted morningglory allows the seed to be viable for more than five and half years. Stephenson et al. (2006) determined pitted morningglory has the ability to morphologically vary with ecotypes having leaf shapes of arrow, heart, a mixture of both, and white or purple flowers. Ecotypes are defined as a population within a species that has developed characteristics in response to a specific environment and retain these characteristics when moved to a different environment (Valentine 1949). Ivyleaf and entireleaf morningglory are similar in habit to pitted morningglory, as vining, summer annuals, but differ in plant morphology. Entireleaf morningglory carries the same species name as ivyleaf morningglory, though it is a variant of different leaf shape. Ivyleaf morningglory and entireleaf morningglory have very similar characteristics such as pubescent stems, a pubescent leaf surface and leaf margin (of which protrudes vertical to the leaf surface), a taproot, and funnel-shaped white or purple flowers, and are facultative self-pollinators (Elmore 1986; Elmore et al. 1990; Burke et al. 2008). The primary difference is ivyleaf morningglory has 3-lobed or ivy-shaped leaves, while entireleaf morningglory has distinctly heart-shaped leaves. Crossings between the two species have shown that ivyleaf has the dominant allele for determination of leaf shape, yet entireleaf morningglory has shown to be the dominant phenotype in the Mississippi Delta Region (Elmore et al. 1986). Research has shown the ability of both plant to produce from 5,000 to 6,000 seeds per plant^{-1} (Crowley and Buchanan 1982). Additionally, entireleaf morningglory ecotypes have been found with differing first flower initiation and leaf trichome number (Klingaman and Oliver 1996). Multiple studies have shown high competitiveness between entireleaf and ivyleaf morningglory species and multiple crops with high herbicidal tolerance causing further issues (Thakar and Singh 1954; Crowley and Buchanan 1978; Mathis and Oliver 1980; Cordes and Bauman 1984; Holloway and Shaw 1996). Interestingly, Price and Wilcut (2007) found ivyleaf morningglory appears to alter its growth response based on surrounding objects with the possibility that the stems preferentially grow towards structures favorable for climbing. The study resulted in morningglory locating and climbing corn 78% of the time when found within 46 cm of the plant (Price and Wilcut 2007).

Objective

The prevalence of morningglory species in corn production systems in Alabama requires recommendations for season-long control, however none exist. HPPD inhibitors can potentially provide producers with an alternate mode of action that could help increase residual weed control of multiple species. Adding HPPD inhibiting herbicides to a herbicide regime could help reduce harvest inefficiencies, save producers time and money by decreasing chemical usage (herbicides, desiccants, etc.), and potentially increase crop yields. Additionally, the low amounts of herbicide active ingredient for HPPD-inhibitor products applied could potentially provide a more environmentally safe option as compared to full rate applications of atrazine. The use of atrazine is a staple herbicide in current systems, but only 2.2 kg ai ha^{-1} may be applied in total per growing season, and continuous questions about the product's health effects could lead to a shift in the amount of product available to use in the future. HPPD-inhibitors could have the potential to reduce the amount of atrazine herbicide use required in corn production systems, while still providing acceptable weed control. Inconsistent information regarding season-long control of morningglory in corn using HPPD inhibitors proves a need for further studies of the subject.

The objective of this study is 1.) to determine the efficacy of HPPD inhibitors, applied with atrazine POST, or following atrazine PRE, in a comprehensive side-by-side comparison for full-season control of morningglory species in Alabama corn 2.)

determine the efficacy of these HPPD inhibitors for secondary full-season weed control of other problematic weeds present.

Materials and Methods

Field experiments were conducted in 2017 and 2018 at the Alabama Agricultural Experiment Station Agricultural Research Unit in Prattville, AL (32.43° N, -86.44° W) and the Sand Mountain Research and Extension Center in Crossville, AL (34.28° N, -85.96°W). The soil type at the Alabama Agricultural Experiment Station Agricultural Research Unit in Prattville, AL is a Lucedale fine sandy loam (fine-loamy, siliceous, subactive, thermic Rhodic Paleudult) with a pH of 6.0 and 1.25% organic matter. The soil type at the Sand Mountain Research and Extension Center in Crossville, AL is a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults) with a pH of 6.2 and 1.25% organic matter. In 2017 at Prattville, corn (*Zea mays* L.) was planted on March 31, 2017 and April 12, 2018 at a rate of 8-9 seed per m row and a 5 cm planting depth. At Crossville, corn was planted on May 9, 2017 and May 5, 2018 at a rate of 5 seed per m row and a 5 cm planting depth. The cultivar planted, planted in both years at both locations, was Pioneer '1197 YHR' (DuPont Pioneer, Johnston, IA). Plot size was 4 rows, with 76.2-cm row spacing by 7.62 m in length. Agronomic practices such as fertilization, determined by soil test analysis, and insect management were applied at both locations using the Auburn University and Alabama Cooperative Extension Service Corn Integrated Pest Management Guide (2018). Herbicide treatments were applied via broadcast using a CO_2- pressurized backpack sprayer with four nozzles calibrated to deliver 140 L ha^{-1} at 262 kPA and 4.83 km h^{-1}. Boom width was 1.9 m with 48 cm nozzle spacing. The nozzle type used was an 110015

TurboDrop® XL Medium Pressure Nozzle (Greenleaf Technologies, Covington, Louisiana). Treatments were applied to V3 and V4 corn at up to a maximum of 30 cm (12 in.) in height, approximately 30 days after planting (DAP). Soil moisture conditions were adequate at application. Dates of corn planting, herbicide applications and corn harvest are presented in Table 1.1 and Table 1.2. Environmental conditions at POST application at both locations for both years are presented in Table 1.3.

The same area was utilized at each location in both years, in areas known for their propensity for heavy morningglory pressure. The primary weed species evaluated were *Ipomoea* spp., *Amaranthus* spp., and *Senna* spp. The main *Ipomoea* spp. located at both locations were pitted, ivyleaf, and entireleaf morningglory. *Amaranthus* spp. observed were Palmer amaranth (*Amaranthus palmeri* L.) at Prattville, AL and a combination of redroot pigweed (*Amaranthus retroflexus* L.) and Palmer amaranth at Crossville, AL. In 2017, sicklepod (*Senna obtusifolia* L.) was evaluated at only the Prattville, AL as there was not sicklepod pressure in the Crossville, AL trial location. In 2018, a combination of sicklepod and coffee senna (*Senna occidentalis* L.) were present at Prattville, while there was sicklepod pressure at the Crossville trial location. Pest growth stage at time of application ranged from cotyledon to 5-15 cm length in *Ipomoea* spp., approximately 5 to 12 cm height in *Amaranthus* spp., and approximately 5 to 10 cm height in *Senna* spp.

Herbicide treatments were split into ten treatments applied POST with atrazine (Aatrex® 4L, Syngenta Crop Protection, Greensboro, NC) applied pre-emergence (PRE) at 1.12 kg ai ha^{-1} and twelve treatments in combination with atrazine and applied POST at 1.12 kg ai ha^{-1}. Treatments with atrazine included in the premixture did not have additional atrazine added in the postemergence tank mix. Herbicide treatments applied

POST included tembotrione (Laudis®, Bayer Crop Science, Research Triangle Park, NC) at 0.092 kg ai ha^{-1}, mesotrione (Callisto® 4L, Syngenta Crop Protection) at 0.105 kg ai ha^{-1}, topramezone (0.0147 kg ai ha^{-1}) + dimethenamid-P (0.738 kg ai ha^{-1}) (Armezon Pro®, BASF Corporation, Research Triangle Park, NC) at .752 kg ai ha^{-1}, S-metolachlor (1.05 kg ai ha^{-1}) + glyphosate (1.05 kg ae ha^{-1}) + mesotrione (0.105 kg ai ha^{-1}) (HalexGT®, Syngenta Crop Protection) at 2.21 kg ai ha^{-1}, thiencarbazone-methyl (0.150 kg ai ha^{-1}) + tembotrione (0.758 kg ai ha^{-1}) (Capreno®, Bayer Crop Science) at 0.91 kg ai ha^{-1}, topramezone (Armezon®, BASF Corporation) at 0.12 kg ae ha^{-1}, S-metolachlor (1.11 kg ai ha^{-1}) + atrazine (1.09 kg ai ha^{-1}) + mesotrione (0.143 kg ai ha^{-1}) (Lexar EZ®, Syngenta Crop Protection) at 2.34 kg ai ha^{-1}, S-metolachlor (1.21 kg ai ha^{-1}) + atrazine (0.570 kg ai ha^{-1}) + mesotrione (0.136 kg ai ha^{-1}) + bicyclopyrone (0.0339 kg ai ha^{-1}) (Acuron®, Syngenta Crop Protection) at 1.96 kg ai ha^{-1}, nicosulfuron (0.034 kg ai ha^{-1}) + mesotrione (0.088 kg ai ha^{-1}) (Revulin Q®, DuPont Crop Protection, Wilmington, DE) at 0.122 kg ai ha^{-1}, isoxaflutole (Balance Flexx®, Bayer Crop Science) at 0.053 kg ai ha^{-1}, and isoxaflutole (0.550 kg ai ha^{-1}) + thiencarbazone-methyl (0.0220 kg ai ha^{-1})(Corvus®, Bayer Crop Science) at 0.077 kg ai ha^{-1}. All treatments, excluding treatments with glyphosate included in the premixture, were applied in combination with glyphosate (Roundup Powermax®, Monsanto Company, St. Louis, MO) at 0.84 kg ae ha^{-1}. Adjuvants were applied according to herbicide manufacturer's label recommendations. The treatments containing the premixtures of topramezone + dimethenamid-P, S-metolachlor + glyphosate + mesotrione, and S-metolachlor + atrazine + mesotrione + bicyclopyrone received a 0.25% V/V amount of non-ionic surfactant adjuvant (Induce®, Helena Agri-Enterprises, Collierville, TN). The premixtures of thiencarbazone-methyl +

tembotrione and nicosulfuron + mesotrione received a 1% V/V amount of crop oil concentrate adjuvant (Agri-Dex®, Helena Agri-Enterprises). The treatment containing topramezone alone received a 1% V/V amount of methylated seed oil adjuvant (MSO® with LECI-TECH, Loveland Products, Ontario, Canada). Corn grain from the plots was harvested using a Kincaid 8-XP Multi-Crop Research Plot Combine (Kincaid Equipment Manufacturing, Haven, KS), equipped with electronic scales and moisture sensor that recorded corn yield in bushels per hectare, adjusted to 56 lb/bu @ 15.5% moisture content.

Visual evaluations were made on a scale of 0-100% with 0 = no control and 100 = complete control (Frans et al. 1986). Weed control was evaluated at 30, 60, and 90 days after treatment (DAT) of the HPPD-inhibitor applications, and at harvest. The atrazine PRE control ratings are also based on the time of HPPD-inhibitor application and not the atrazine PRE application. The ratings of atrazine PRE will reflect an additional 30 days after treatment (e.g 30 DAT rating is 60 days after initial atrazine PRE treatment). The trial design was an incomplete block design with a split-plot treatment arrangement and four replications. The null hypothesis of this project was that the main interaction of herbicide treatment * atrazine would not significantly affect late season morningglory control. Treatment effects were determined by ANOVA using the *lmer* (linear mixed effect regression) function in the *lme4* package (Bates et al. 2015) in R version 1.1.456 (R Development Core Team 2018) to test for main effects and all interactions. Replication and location were fitted as random effects. Fixed effects were fitted as treatment, the addition or exclusion of atrazine, and year. Initial analysis of visual weed control was a year * herbicide * atrazine main effect interaction to determine if there was a significant year effect. Year was determined to not be a significant factor, or a part of a year X herbicide * atrazine interaction, so both trial years were pooled for further analysis. This is acceptable as environments (eg location and year) are commonly fitted as random effects in models for statistical analysis (Blouin et al. 2011). Analysis of treatment effects produced a significant herbicide * atrazine interaction only in the at-harvest *Ipomoea* spp. rating. The remaining control rating timings across all weed species underwent further analysis for treatment as the main effect. Multiple pairwise comparisons between treatments were performed using the "multcompView" package in R (Graves et al. 2015). Each visual weed control rating, as well as yield were evaluated separately, and means were separated using Fisher's Protected LSD at $P \leq 0.05$ using the *lsmeans* function in the *lsmeans* package (Lenth 2016).

Results and Discussion

Ipomoea species control

The control data presented for the 30 DAT, 60 DAT, and 90 DAT ratings on *Ipomoea* spp. control are the results of total combined treatments with and without atrazine, due to a lack of statistical effects of year, location, or atrazine and their interactions, with the exception of those HPPD herbicide treatments including atrazine in the postemergence premix. For the purposes of these results, 100-90% control will be described at excellent control compared to non-treated checks, 89-80% will be described as good control, 79-70% will be described as fair control, and 69-60% and below will be described as poor control. Results are presented in Table 1.4.

At 30 DAT, the premixture of S-metolachlor plus atrazine plus mesotrione provided the highest numerical control at 98%, with similar control from treatments consisting of the premixture S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone, mesotrione, the premixture isoxaflutole plus thiencarbazone-methyl, the premixture S-metolachlor plus glyphosate plus mesotrione, and the premixture nicosulfuron plus mesotrione all had 97% control. The premixture of tembotrione plus thiencarbazone-methyl and tembotrione were also excellent at 96% and 95% control, respectively, while the only HPPD-inhibiting herbicide to have a significantly different control was topramezone at 93%, which also still constitutes as excellent control, but not as high numerically as the other HPPD-inhibitors. The application of atrazine PRE produced the lowest *Ipomoea spp.* control rating with a poor control at 63% compared to the non-treated check ($P \leq 0.05$)

At 60 DAT, a similar comparison of results was observed between HPPD inhibitors while a slight decrease in control occurred. Excellent control continued to be provided by the premixture of S-metolachlor plus atrazine plus mesotrione, along with the premixture isoxaflutole plus thiencarbazone-methyl, the premixture S-metolachlor plus glyphosate plus mesotrione, and the premixture nicosulfuron plus mesotrione at 95% control of *Ipomoea* spp. The premixture of S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone, mesotrione, and the premixture of tembotrione plus thiencarbazone-methyl was similar (94% control). The premixture of topramezone plus dimethenamid-P and tembotrione lowered in control, compared to the 30 DAT rating, to 91% and 90%, respectively, yet retained their level of significance. Topramezone alone continued to be the only HPPD inhibitor significantly lower control at 88%, though this is still considered to be good weed control. The atrazine PRE alone application was below poor in control at

51%, significantly less than HPPD inhibitor applications and further below the acceptable limit of weed control.

Comparisons tend to be similar at the 90 DAT control rating with the premixture S-metolachlor plus atrazine plus mesotrione, the premixture of S-metolachlor plus glyphosate plus mesotrione, the premixture of nicosulfuron plus mesotrione, and the premixture of S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone ranging from 93% to 94% and maintain excellent control. The premixture of topramezone plus dimethenamid-P, isoxaflutole, mesotrione, the premixture of tembotrione plus thiencarbazone-methyl, and the premixture of isoxaflutole plus thiencarbazone-methyl still maintain good to excellent control ranging from 89% to 92%. We see a significant difference at this control rating for tembotrione (83%) which is a reduction compared to the 60 DAT rating. Topramezone was statistically similar in control to tembotrione at 83%, following its trend of statistically lower control compared to the other HPPD inhibitors throughout the first 60 days, yet retaining good control.

At harvest (Table 1.5), analysis of HPPD herbicide treatments * atrazine main effect showed significant effects of these factors with no interactions. Atrazine was left as a main effect as compared to the previous *Ipomoea* spp. control rating analyses where atrazine was dropped from the model after no significant atrazine or HPPD-herbicide treatment * atrazine interaction was found. Excellent control ratings included treatments of the premixture topramezone plus dimethenamid-P with atrazine, the premixture of tembotrione plus thiencarbazone-methyl with atrazine, the premixture S-metolachlor plus glyphosate plus mesotrione with and without atrazine, the premixture of S-metolachlor plus atrazine plus mesotrione, and the premixture of nicosulfuron plus mesotrione with and without maintained resulted in excellent *Ipomoea spp.* control ranging from 91% to 94%. Many treatments produced a good control rating at this timing. The premixture of S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone and mesotrione with and without atrazine all provided 87-88% control, and isoxaflutole plus thiencarbazone-methyl without atrazine produced 87% *Ipomoea* spp. control. Topramezone with atrazine, isoxaflutole with atrazine, and the premixture of isoxaflutole plus thiencarbazone-methyl all had 85% control, still good control. Our treatment control ratings start to decline into fair control status for several treatments by harvest. The premixture of thiencarbazone-methyl plus tembotrione drops to 80% control. Isoxaflutole without atrazine has fair control of 79%, while the premixture of topramezone plus dimethenamid-P without atrazine was 76% control and tembotrione with atrazine was 75% control. Though providing from excellent to fair control, the at harvest results described have still maintained similar levels of significance. A drop in significant control is seen as tembotrione without atrazine provided only 70%, which is on the edge of fair control. Tembotrione without atrazine is comparable with topramezone without atrazine as a poor control rating of 65% was observed at harvest. Atrazine PRE continues its decline in control over the full season into very poor weed control as it had only 36% control at harvest.

The 30, 60, and 90 DAT analysis results provided insight on the effectiveness of the HPPD-inhibitors. *Ipomoea* spp. control ranged from 83% to 98% throughout this timeframe. Although the primary focus of this trial was not exclusively looking at atrazine alone, its results were presented. As expected, the atrazine PRE application was worse in control as the season progressed. The at-harvest rating provided finer insight to the HPPD-inhibitors with and without atrazine. A large portion of HPPD-herbicide treatments performed similarly with and without atrazine, but some varied. Topramezone with atrazine resulted in 85% control of *Ipomoea* spp. while topramezone without atrazine resulted in poor control at 65% on *Ipomoea* spp. at harvest. Additionally, the premixture of topramezone plus dimethenamid-P, with and without atrazine, was 91% and 76%, respectively, though there was not a statistical difference. The synergistic effects, as previously described, of combining atrazine with HPPD-inhibitors POST may be shown in topramezone treatment results (Armel et al. 2003; Armel et al. 2005; Johnson et al. 2002; Hugie et al. 2008; Sutton et al. 2002; Williams et al. 2011).

Tembotrione performed fair to borderline poor at harvest, with and without atrazine, respectively. This is contradictory to Stephenson et al. (2015) as they saw 92% control of entireleaf morningglory at harvest with tembotrione plus atrazine, while also showing tembotrione without atrazine at 79% control at harvest. Our trials' results show lower percentages of control (75% control with atrazine and 70% control without atrazine, at harvest), though this could be due to populations dominated by other morningglory species than entireleaf morningglory which may have responded to these treatments differently. Additionally, their entireleaf morningglory control results of thiencarbzone-methyl plus tembotrione POST, with and without atrazine, were 93% and 85% at harvest (Stephenson et al. 2015). These results are similar to our results of 91% and 80% control of *Ipomoea* spp., although their rate of atrazine was double the rate that was used in this trial. Bararpour et al. (2011) provided similar results of 90-100% of control of entireleaf and pitted morningglory with application combinations of thiencarbazone-methyl plus either atrazine, glufosinate, or glyphosate. Stephenson and

Bond (2012) have reported that isoxaflutole and the premixture of thiencarbazone-methyl plus isoxaflutole PRE have the ability to control entireleaf morningglory 84% and 85%, respectively, 20 weeks after planting (WAP) with slightly greater control with atrazine included. Though this trial has multiple morningglory species and applications were POST, similar control results show that the application timing can vary and morningglory species can still be adequately controlled.

Stephenson et al. (2004), though they did not take a control rating at harvest, produced similar results for morningglory control 6 weeks after emergence (WAE) using mesotrione. Mesotrione treatments controlled pitted and entireleaf morningglory, at mesotrione rates of 70, 105, and 140 g ai/ha^{-1}, with or without atrazine (Stephenson et al. 2004). They concluded that that adding atrazine in the POST treatment did not significantly affect control of these two morningglory species. Thomas et al. (2004) recorded greater than 95% control of *Ipomoea* spp. in the late season with atrazine applied PRE followed by glyphosate plus mesotrione POST, which is one the same treatments as our study. Our study only reported 88% control of *Ipomoea* spp. for the same treatment, though this is still acceptable control. Grichar et al. (2017) reported 82% control 50 DAT of pitted morningglory with the premixture of mesotrione plus S-metolachlor plus glyphosate, less than the 92% control at harvest reported in this trial. Some HPPD inhibitors that combined multiple MOAs had slightly higher *Ipomoea* species control at harvest. This study serves to provide more information, along with previous research, that many of these HPPD inhibitors applied POST, in combination with multiple MOAs or alone and with or without atrazine POST, would likely provide options for Alabama producers looking for greater late season *Ipomoea* species control than with atrazine alone.

Amaranthus species control

HPPD-inhibitor control of *Amaranthus* spp. was analyzed at the 30, 60, 90 DAT, and at harvest. There was no significant effect of atrazine or HPPD-herbicide treatments * atrazine, so significant herbicide treatment effects were analyzed. Results for *Amaranthus* species control are presented in Table 1.6.

At 30 DAT, each treatment containing an HPPD-inhibiting herbicide had excellent control of 98 to 99%. Herbicide treatments with 99% control included the premixture of S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone, topramezone plus dimethenamid-P, tembotrione plus thiencarbazone-methyl, S-metolachlor plus glyphosate plus mesotrione, tembotrione, and nicosulfuron plus mesotrione. Topramezone, isoxaflutole, mesotrione, isoxaflutole plus thiencarbazone-methyl, and S-metolachlor plus atrazine plus mesotrione all provided 98% control of *Amaranthus* spp. compared to the non-treated check. Atrazine PRE had fair control at 75% compared to the non-treated check, and was the only treatment significantly different from the others.

The 60 and 90 DAT control rating produced the same general control. Control percentages ranged from 96% to 98% across all treatments containing HPPD-inhibitors. At harvest, all treatments with HPPD inhibitors continue to provide excellent control with numerically the lowest percentage provided by isoxaflutole at 95%. The atrazine PRE treatment declined into poor control from 66% at 60 DAT to 61% at harvest, and again was the only treatment significantly different from the others.

All treatments containing HPPD inhibitors provided excellent control throughout the season into harvest. Plant counts were not taken, therefore some areas of the fields could have varied in density of *Amaranthus* spp., although the non-treated plots had a low to medium visual density of 4-6 plants/m^{-1} at end of season. Previous studies have reported the combination product of thiencarbazone-methyl plus tembotrione with atrazine as being effective at controlling or suppressing Palmer amaranth 80%- 100%. (Stephenson et al. 2015; Bararpour et al. 2011; Bullington et al. 2009; Robinson and Bean 2010). Simkins et al. (2006) reported tembotrione POST at 92 g ai ha^{-1} controlling Palmer amaranth 95% to 100% at 21 DAT and 40 DAT. Stephenson and Bond (2012) reported the addition of atrazine to thiencarbazone-methyl plus isoxaflutole PRE was needed for at least 90% control at 140 DAT. There has been confirmation of Palmer amaranth resistance to both HPPD-inhibitors and atrazine, though, resistant populations were seemingly not represented in this trial as control was 95% to 98% at harvest (Heap 2018). Redroot pigweed has been established as a major weed in corn production (Knezevic et al. 1994; Williams et al. 2008). Synergistic responses from the addition of atrazine to mesotrione POST for redroot pigweed control have been reported (Woodyard et al. 2009), though not being apparent in this study. Tembotrione, applied with and without atrazine, has been reported to control redroot pigweed 85% and 61%, respectively, while also improving overall weed control when combined with atrazine. Redroot pigweed was only identified at Crossville, AL and populations were similar to Palmer amaranth in density. Though no comprehensive plant counts were taken, non-treated areas of the field showed a low to medium density of naturally established redroot pigweed population. Comparison of the non-treated plots to treated plots at end of season and the analysis data presented suggests that HPPD-inhibitors are effective at suppressing *Amaranthus* spp. growth until harvest.

Senna species control

Senna spp. (mostly sicklepod, specifically) are competitive summer annuals that can develop dense populations due to prolific seed production that can form persistent seed banks due to their hard seed coats (Street et al. 1981; Thomas et al. 2005; Isaacs et al. 1989; Creel et al. 1968).The effectiveness of HPPD-inhibitors on *Senna* spp. was evaluated at Prattville, AL for years 2017 and 2018, and at Crossville, AL in year 2018. There was not a significant effect of atrazine or HPPD-herbicide treatment * atrazine, so significant herbicide effect was analyzed. Control ratings were collected at 30, 60, 90 DAT, and at harvest. Results for *Senna* species control are presented in Table 1.7.

The 30 DAT control rating saw no significant differences between HPPD-inhibitor treatments. The treatments all produced excellent control ratings. Control ranged from 94%- 95% control with the treatments isoxaflutole, the premixture of S-metolachlor plus glyphosate plus mesotrione, and the premixture of S-metolachlor plus atrazine plus mesotrione, and S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone. The remaining treatments ranged from 90% to 93% of *Senna* spp. Atrazine PRE at the 30 DAT rating had the only significantly different control percentage at 59%.

60 DAT, most treatments fell into the 83% to 89% range. S-metolachlor plus atrazine plus mesotrione, S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone, and isoxaflutole all continued to have excellent control at 92%, 90%, and 90%, respectively. Topramezone drops in control from 90% to 83% from 30 DAT to 60

DAT, while tembotrione plus thiencarbazone-methyl drops from 91% to 83% from 30 DAT to 60 DAT, though these still provide good control.

90 DAT, the premixture of S-metolachlor plus atrazine plus mesotrione and S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone continue to have excellent to good *Senna* spp. control at 90% and 88%, respectively. Isoxaflutole has good control at 89%, along with nicosulfuron plus mesotrione at 87% and S-metolachlor plus glyphosate plus mesotrione at 86%. Mesotrione drops slightly from 89% at 60 DAT to 85% at 90 DAT. Similarly, isoxaflutole plus thiencarbazone-methyl drops from 88% at 60 DAT to 84% at 90 DAT. Topramezone and topramezone plus dimethenamid-P drop slightly in *Senna* spp. control to 82%. Tembotrione treatment effect drops from 86% at 60 DAT to 81% at 90 DAT. Interestingly, the premixture tembotrione plus thiencarbazone-methyl drops from 91% at 30 DAT to a fair control rating of 77% at 90 DAT.

At harvest, results show a decrease of most treatments into a fair to poor control range of *Senna* spp. S-metolachlor plus atrazine plus mesotrione has been the most consistent with control dropping from 95% at 30 DAT to 81% at harvest. S-metolachlor plus atrazine plus mesotrione plus bicyclopyrone, isoxaflutole, S-metolachlor plus glyphosate plus mesotrione, and nicosulfuron plus mesotrione still have fair control at 76%. Mesotrione drops to 73% at harvest after having 85% control at 90 DAT. Isoxaflutole plus thiencarbazone-methyl drops to 71% at harvest from 84% at 90 DAT. Both topramezone and tembotrione treatments declined to 70%. Two treatments containing HPPD-inhibitors have poor control of *Senna* spp. at harvest. Topramezone plus dimethenamid-P lowers in control to 67% at harvest from 82% at 90 DAT. Lastly, tembotrione plus thiencarbazone-methyl saw the most drastic control result with 61% at harvest compared to 77% at 90 DAT and 91% at 30 DAT. Atrazine PRE had the only significantly lower control percentage at 24%, dropping from 59% at 30 DAT.

All control rating results described a general decrease in *Senna* spp. control as the season progressed. There were no statistical differences between HPPD-herbicide treatment control ratings analyzed. Only rating *Senna* spp. in three trial locations over the two years may have been an influencing factor on control rating analysis. Information on control of *Senna* spp. with HPPD-inhibitors in corn is limited. Studies have reported 96% control of sicklepod using premixtures containing mesotrione, though these treatments were also in combination with or following pyroxasulfone herbicide (Long-chain Fatty Acid Inhibitor) (Hardwick 2013). Some treatments in this trial containing products that combined multiple MOAs (e.g. S-metolachlor, atrazine, mesotrione, bicyclopyrone, glyphosate) tended to have a slightly higher control percentage of control of this difficult to control weed species at harvest. Further sicklepod control studies could be explored as there is a lack of clear information for the use of HPPD-inhibitors as an effective control method or lack thereof.

Yield

There were no significant differences in corn grain yields between HPPD inhibitor treatments (Table 1.8). The non-treated check alone had a significant difference from treated plots with a yield of 8411 kg ha^{-1}. Atrazine PRE was the lowest yielding treated plot at 9,729 kg ha^{-1}, approximately 738 kg ha^{-1} lower in yield than the treated plot average of 10,477 kg ha^{-1}., although not statistically significant. All other HPPD-herbicide treated plot yields ranged from 10,294 to 10,859 kg ha^{-1}.

Conclusions

Estimated yield losses for corn, with no weed control methods established, are estimated at ≤85% due to problematic weed competition with a loss of productivity and quality of grain harvested (Galon et al. 2010; Carvalho et al. 2007). Several of these HPPD-inhibiting herbicides have shown to have the capability of providing long and consistent full-season control of *Ipomoea* spp. and other problematic weeds in Alabama field corn production. In general, products containing multiple MOAs provided the longest, most consistent control of *Ipomoea* spp. Though, several standalone HPPD-inhibitor products provided fair to good control at harvest. Excellent *Amaranthus* spp. control was established across all treatments. Most treatments produced fair *Senna* spp. control at harvest, with the exception of the premixture S-metolachlor plus atrazine plus mesotrione, which had the highest numerical control rating of 81% at harvest. Further studies could be attempted to establish greater control of *Senna* spp. in field corn. Lastly, yields were statistically the same across all herbicide treatments compared to the non-treated check. The addition of atrazine POST could be a matter of producer preference as many control ratings did not have a significant effect of the addition of atrazine POST. Though, there were some differences in morningglory control at harvest by some HPPD-inhibitors with atrazine POST and without (atrazine PRE) atrazine POST. This study provides additional information about potential weed species control by HPPD-inhibitors in field corn with the conclusion that the use of HPPD-inhibitors is more beneficial than no chemical control at all.

Table 1.1. Corn planting, herbicide application and corn harvest dates at Prattville Agricultural Research Unit, Prattville, AL.

		Herbicide Application		
Year	Corn Planting	PRE	POST	Corn Harvest
2017	31-Mar	31-Mar	2-May	14-Sep
2018	12-Apr	12-Apr	17-May	20-Sep

Table 1.2. Corn planting, herbicide application and corn harvest dates at Crossville, AL (SMREC).

		Herbicide Application		
Year	Corn Planting	PRE	POST	Corn Harvest
2017	9-May	9-May	20-June	22-Sep
2018	5-May	5-May	30-May	20-Sep

Table 1.3 Environmental conditions at application at both locations for both years.

Environmental Conditions at Application	Crossville, AL		Prattville, AL	
	2017	2018	2017	2018
Air Temperature (C°)	27.8	25.6	25.5	30
Soil Temperature (C°)	20	22.2	20	21.1
Relative Humidity (%)	54	90	40	47
Wind Speed (km/h)	6.44	9.66	14.5	12.9
Cloud Cover (%)	80	85	20	75
Rainfall (cm)	36	46	97	69

Table 1.4 Ipomoea species control at 30, 60, and 90 DAT for the 2017/2018 growing season[1, 4, 5]

Ipomoea spp. Control 2017/2018

Herbicide[2]	30 DAT[3] --% --	60 DAT --%--	90 DAT --%--
Non-treated	0d	0d	0d
atrazine PRE	62c	51c	41c
S-metolachlor + atrazine+ mesotrione+ bicyclopyrone	97a	94ab	93a
topramezone	93b	88b	83b
topramezone +dimethenamid-P	96a	91ab	89ab
isoxaflutole	96a	92ab	90ab
mesotrione	97a	94ab	91ab
tembotrione+ thiencarbazone-methyl	96a	94ab	91ab
isoxaflutole + thiencarbazone-methyl	97a	95a	92a
S-metolachlor+ glyphosate+ mesotrione	97a	95a	94a
tembotrione	95ab	90ab	83b
S-metolachlor + atrazine+ mesotrione	98a	95a	94a
nicosulfuron + mesotrione	97a	95a	93a

[1] Data was pooled across four experiments in two trial years and two locations.

[2] All herbicide treatments were applied at their respective 1X rates. Glyphosate was applied with all treatments that did not contain glyphosate in the premix. Trade names and rates for all herbicides are described in the Materials and Methods section.

[3] *Ipomoea* species evaluated for control consisted mainly of pitted, entireleaf, and ivyleaf morningglory.

[4] Means followed by the same letter in each column are not significantly different at $P \leq 0.05$

[5] All rating analysis p-values= <0.0001 for herbicide main effect

Table 1.5 *Ipomoea* species control by, HPPD inhibitors with and without atrazine, at harvest for the 2017 and 2018 growing season[1, 4, 5]

Ipomoea spp. at harvest Control 2017/2018

Herbicide[2]	At Harvest[3]	
	Atrazine	
	with[5]	without
	-----------------%----------------	
Non-treated	0e	0e
atrazine PRE	-	36d
topramezone	85abc	65c
topramezone +dimethenamid-P	91a	76abc
isoxaflutole	85abc	79abc
mesotrione	87ab	88abc
thiencarbazone-methyl + tembotrione	91a	80abc
isoxaflutole + thiencarbazone-methyl	85abc	87ab
S-metolachlor+ glyphosate+ mesotrione	92a	92a
tembotrione	75abc	70bc
nicosulfuron + mesotrione	93a	91a
S-metolachlor + atrazine+ mesotrione+ bicyclopyrone	-	87ab
S-metolachlor + atrazine+ mesotrione	-	94a

[1] Data was pooled across four experiments in two trial years and two locations.

[2] All herbicide treatments were applied at their respective 1X rates. Glyphosate was applied with all treatments that did not contain glyphosate in the premix. Trade names and rates for all herbicides are described in the Materials and Methods section.

[3] *Ipomoea* species evaluated for control consisted mainly of pitted, entireleaf, and ivyleaf morningglory..

[4] Means followed by the same letter in each column are not significantly different at P≤0.05.

[5]Significant herbicide X atrazine interaction p-value= 0.046, herbicide main effect p-value= <0.0001, atrazine main effect p-value= 0.0015

Table 1.6 *Amaranthus* species control at 30, 60, 90 DAT, and at harvest in the 2017 and 2018 growing season[1, 4, 5]

Amaranthus spp. Control 2017/2018

Herbicide[2]	30 DAT[3]	60 DAT	90 DAT	At Harvest
	--------------------------	%	----------------------	
Non-treated	0c	0c	0c	0c
atrazine PRE	75b[5]	66b	61b	61b
S-metolachlor + atrazine+ mesotrione+ bicyclopyrone	99a	98a	98a	98a
topramezone	98a	97a	98a	98a
topramezone +dimethenamid-P	99a	98a	98a	97a
isoxaflutole	98a	97a	97a	95a
mesotrione	98a	97a	96a	96a
thiencarbazone-methyl + tembotrione	99a	98a	98a	97a
isoxaflutole + thiencarbazone-methyl	98a	97a	97a	97a
S-metolachlor+ glyphosate+ mesotrione	99a	98a	98a	98a
tembotrione	99a	98a	97a	97a
S-metolachlor + atrazine+ mesotrione	98a	97a	96a	96a
nicosulfuron + mesotrione	99a	97a	98a	98a

[1] Data was pooled across four experiments in two trial years and two locations.

[2] All herbicide treatments were applied at their respective 1X rates. Glyphosate was applied with all treatments that did not contain glyphosate in the premix. Trade names and rates for all herbicides are described in the Materials and Methods section.

[3] *Amaranthus* species evaluated for control consisted mainly of Palmer amaranth and redroot pigweed

[4] Means followed by the same letter in each column are not significantly different at P≤0.05.

[5] All rating analysis p-values= <0.0001 for herbicide main effect

Table 1.7 *Senna* species control at 30, 60, 90 DAT, and at harvest in the 2017 and 2018 growing season[1, 4, 5]

Senna spp. Control 2017/2018

Herbicide[2]	30 DAT[3]	60 DAT	90 DAT	At Harvest
	-------------------------	%	-----------------------	
Non-treated	0c	0c	0c	0c
atrazine PRE	59b[5]	57b	46b	24b
S-metolachlor + atrazine+ mesotrione+ bicyclopyrone	93a	88a	88a	76a
topramezone	90a	83a	82a	70a
topramezone +dimethenamid-P	90a	84a	82a	67a
isoxaflutole	94a	90a	89a	76a
mesotrione	93a	89a	85a	73a
thiencarbazone-methyl + tembotrione	91a	83a	77a	61a
isoxaflutole + thiencarbazone-methyl	93a	88a	84a	71a
S-metolachlor+ glyphosate+ mesotrione	95a	89a	86a	76a
tembotrione	92a	86a	81a	70a
S-metolachlor + atrazine+ mesotrione	95a	92a	90a	81a
nicosulfuron + mesotrione	93a	89a	87a	76a

[1] Data was pooled across four experiments in two trial years and two locations.

[2] All herbicide treatments were applied at their respective 1X rates. Glyphosate was applied with all treatments that did not contain glyphosate in the premix. Trade names and rates for all herbicides are described in the Materials and Methods section.

[3] *Senna* species evaluated for control consisted mainly of sicklepod and coffee senna

[4] Means followed by the same letter in each column are not significantly different at P≤0.05.

[5] All rating analysis p-values= <0.0001 for herbicide main effect

Table 1.8 Corn grain yields for the 2017 and 2018 growing season [1, 3, 4]

Corn Yield 2017/2018

Herbicide[2]	Yield
	--kg/ha^{-1}--
Non-treated	8411b
atrazine PRE	9729ab
S-metolachlor + atrazine+ mesotrione+ bicyclopyrone	10671a
topramezone	10483a
topramezone +dimethenamid-P	10545a
isoxaflutole	10357a
mesotrione	10420a
thiencarbazone-methyl + tembotrione	10545a
isoxaflutole + thiencarbazone-methyl	10249a
S-metolachlor+ glyphosate+ mesotrione	10859a
tembotrione	10733a
S-metolachlor + atrazine+ mesotrione	10545a
nicosulfuron + mesotrione	10419a

[1] Data was pooled across four experiments in two trial years and two locations.

[2] All herbicide treatments were applied at their respective 1X rates. Glyphosate was applied with all treatments that did not contain glyphosate in the premix. Trade names and rates for all herbicides are described in the Materials and Methods section.

[3] Means followed by the same letter in each column are not significantly different at $P \leq 0.05$.

[4] Yield analysis p-value= 7.08e-07

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