EVALUATION OF FLUMIOXAZIN EFFICACY FOR ANNUAL BLUEGRASS CONTROL IN WARM-SEASON TURFGRASSES

BY

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(Under the Direction of Patrick McCullough)

ABSTRACT

Flumioxazin is a protoporphyrinogen oxidase inhibitor that offers an alternative mechanism of action to other chemistries for postemergence annual bluegrass (*Poa annua* L.) control with residual summer annual weed control in bermudagrass (*Cynodon dactylon* (L.) Pers.). However, comprehensive research is warranted to effectively utilize flumioxazin in warm-season turfgrass weed control programs. This research evaluated the effects of air temperature, application placement, spray adjuvants, and tank-mixtures with other herbicides on flumioxazin efficacy in turfgrass.

Temperatures >10° C and root uptake were critical for maximizing flumioxazin efficacy. Adjuvants did not improve postemergence annual bluegrass control from flumioxazin alone, but tank-mixtures with other herbicides enhanced control. Late winter applications of flumioxazin before greenup caused minimal injury (<20%) to four of the five turfgrasses evaluated. Practitioners may use flumioxazin to avoid herbicide resistance of annual bluegrass populations in long-term management, and provide effective preemergence summer annual grassy weed control.

INDEX WORDS: Flumioxazin, Turfgrass, Herbicide, Annual bluegrass (*Poa annua* L.), Bermudagrass (*Cynodon dactylon* (L.) Pers.), Protoporphyrinogen oxidase

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DEDICATION

This thesis is dedicated to my mother, Ann Reed, and my father, Randall Reed.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Annual Bluegrass

Annual bluegrass (*Poa annua* L.) is a problematic winter annual weed that reduces turf aesthetics and functionality. Annual bluegrass has a bunch-type growth habit, light green color, and abundant seedhead production. Additionally, annual bluegrass has poor stress tolerances and population decline in late spring reduces turf quality (Beard 1970; Lush 1989).

Annual bluegrass is distributed throughout the world and can be found in subarctic, temperate, and subtropical climates. It is a native of Europe and believed to have originated from a cross between an annual, *Poa infirma* H. B. K., and a perennial, *Poa supina* Schrad., in the northern Mediterranean (Beard et al. 1978; Gibeault 1967; Koshy 1969;Turgeon 1999; Tutin 1952, 1954). Annual bluegrass belongs to the *Poaceae* family, *Festucoideae* subfamily, and *Festuceae* tribe and considered to be an allotetraploid with 28 chromosomes (2n=4x=28) (Turgeon 1999; Tutin 1957).

Annual bluegrass is a clump forming species with glabrous leaves and boat-shaped leaf tips (Hall 2009). During establishment annual bluegrass seedlings may have competitive morphological growth advantages, such as leaf blade sizes (Cattani et al. 2002). The plant has a membranous ligule and open, pyramidal panicle seedheads. The spikelets are approximately 4 to 6 mm long, and will produce 3 to 6 flowers each. Root systems are fibrous and shallow with plants growing larger through tillering (Hall 2009; Radford et al. 1968). These characteristics distinguish annual bluegrass as an unsightly weed in polyculture with most turfgrasses.

Both annual (*Poa annua* ssp. *annua*) and perennial (*Poa annua* ssp. *reptans*) subspecies of *Poa annua* exist (Tutin 1957). Extensive biological and morphological variability occurs in annual bluegrass subspecies that may be attributed to management and ecological factors (Lush 1989; McElroy et al. 2002; McElroy et al. 2004). Perennial subspecies may have better stress tolerances than annual subspecies and are often found in intensively managed turfgrasses, such as golf course putting greens. Perennial subspecies are prevalent in shady or highly trafficked areas with compacted soil and are more prostrate in growth, than annual subspecies, and root at nodes of tillers or stolons (Hovin 1957; Johnson and Murphy 1996; McCullough 2012). Perennial subspecies of annual bluegrass produce fewer seeds than annual subspecies but may spread and reproduce through vegetative stems (Johnson et al. 1993; Johnson and White 1997).

Annual bluegrass is capable of germinating year round in certain microenvironments, but most commonly germinates in fall when temperatures are ≤ 20° C (Kaminski and Dernoeden 2007; McElroy et al. 2004). After fall germination, annual bluegrass overwinters in a vegetative state, resumes growth in spring, and produces seed until early summer. Dormant annual bluegrass seeds may remain viable for more than six years and could germinate upon favorable environmental conditions such as adequate moisture and soil temperatures (Allen et al. 1993).

Annual bluegrass lacks aesthetics and functionality of traditional turfgrass species. Presence of annual bluegrass in other turfgrass species is unsightly due to its lighter green color and coarser leaf texture (Beard et al. 1978; Vargas 1996). Moreover, annual bluegrass is a prolific seedhead producer even at low mowing heights and can disrupt turf uniformity (Beard et al. 1978; Johnson and Bundschuh 1993).

Annual bluegrass has poor abiotic stress tolerance and is less tolerant to traffic stress from weak rooting relative to turfgrasses (Beard et al. 1978). Annual bluegrass has poor tolerance to heat stress and requires intensive water and fertility management during the summer for successful culture (Beard 1970; Lush 1989). Decline of annual bluegrass in summer may reduce turf quality and increase requirements for water, fungicides, and intensive management.

In the Southeastern United States, annual bluegrass often dies in late spring and may leave voids in turf. (Beard et al. 1978). Annual bluegrass is susceptible to diseases during warm weather in late spring and summer. Foliar anthracnose (*Colletortrichum graminicola* (Ces.) Wils.), a fungus active during the summer months, is destructive to annual bluegrass (Danneberger et al. 1983; Smiley et al. 2005; Turgeon et al. 2004). Annual bluegrass is also susceptible to bacterial wilt (*Xanthomonas campetris*) and other common turf diseases such as dollar spot (*Sclerotinia homeocarpa* F.T. Bennett), and can be damaged by annual bluegrass weevil (*Listonotus maculicollis* Dietz) in the northern United States (Turgeon 1999; Smiley et al. 2005; Vittum 2006). Annual bluegrass sensitivity to disease, insects, and environmental stress often requires more pesticide use than most turfgrasses for successful culture, and thus, controlling annual bluegrass is often more desirable in mixed turfgrass stands.

Annual bluegrass is often cultivated as a desirable turf species. Annual bluegrass withstands close mowing, and produces a high number of tillers (Lush 1988). In cool-humid regions, annual bluegrass may be cultured as a turf, but poor disease, drought, and wear tolerances create challenges for long-term culture.

Cultural Control of Annual Bluegrass

A healthy, dense turfgrass is often competitive with annual bluegrass and may help control populations. Cultural practices that weaken turf will allow annual bluegrass to establish and compete for light, water, and nutrients. Excessive water, compacted soils, disease, scalping, or wear will reduce turfgrass competition and increase potential annual bluegrass growth (Beard 1970; Younger 1959). Turfgrass mowed frequently during periods of vigorous growth helps prevent scalping that leads to canopy thinning (McCullough 2012). Although easily injured under certain conditions, annual bluegrass is considered an opportunistic grass that often invades turfgrass stands weakened by improper management (Beard et al. 1978).

Annual bluegrass thrives under moist, fertile soils in cool or shaded environments when pests are adequately controlled (Beard et al. 1978; McCarty et al. 2005). Annual bluegrass grows well under short day lengths and cool conditions, and may out compete other turf species during late fall and early spring. The ability of a desired turfgrass species to compete with annual bluegrass may be improved through practices, such as deep and infrequent irrigation that encourages root development. Avoiding irrigation until desirable turfgrass species exhibit initial drought stress symptoms can help reduce soil moisture for potential annual bluegrass infestations (McCullough 2012).

Turfgrass growth and competition with annual bluegrass may increase with practices that avoid soil compaction. Vertical mowing and aerification should be timed to avoid peak annual bluegrass germination (Beard 1978). Core aerifications should be conducted during active growth for favorable turfgrass recovery. However, exposed soil following aerifications may allow for annual bluegrass inhabitation (Beard 1978; McCullough 2012).

Annual bluegrass has proven to thrive in well-maintained turfgrass stands. Bogart and Beard (1973) noted optimum cutting heights of 2.5 cm for maximum populations. Raised mowing heights during peak annual bluegrass germination may encourage turf competition to reduce potential infestations. Lowered mowing heights may predispose turf to stress and reduce competition with annual bluegrass populations. Although returning clippings is often recommended as a cultural practice to recycle nutrients to the soil, removal of clippings may be useful to reduce the return of annual bluegrass seed to soil. Annual bluegrass seedheads returned to the soil with clippings may result in subsequent germination of seed, and thus, increase potential for populations in mixed stands. Returning clippings to soil of mixed turfgrass stands increases annual bluegrass cover compared to when clippings are removed and viable annual bluegrass seed is reduced (Gaussoin and Branham 1989).

Fertilization can impact annual bluegrass populations. Excessive nitrogen and phosphorus or an imbalance of nutrients may increase annual bluegrass growth (Goss et al. 1975). Reduction of nitrogen fertilization during peak annual bluegrass germination and periods of vigorous growth as well as during periods when desirable warm-season turfgrasses are dormant may limit annual bluegrass spread and survival.

Chemical Control of Annual Bluegrass

Chemical control with proper cultural practices is often necessary to effectively control annual bluegrass. Preemergence herbicides are applied prior to germination of annual weeds and may control annual bluegrass (Goss 1964; McCarty et al. 2005). Preemergence herbicides such as dithiopyr, pendimethalin, and prodiamine inhibit cell division of immature roots and shoots of susceptible annuals germinating from seed (McCarty et al. 2005). Annual bluegrass has developed resistance to mitotic inhibiting herbicides and other preemergence herbicides such as ethofumesate that inhibit fatty acid synthesis (Cutulle et al. 2009; Heap 1997; Isrigg et al. 2002; Lowe et al. 2001).

Preemergence herbicides have residual soil activity, but provide inconsistent levels of annual bluegrass control if germination is altered or extended by environmental factors (Johnson

1977; McElroy et al. 2004). Preemergence herbicides control newly germinated annual bluegrass, but treatments do not eradicate established plants or control perennial biotypes (Bingham and Shaver 1979; Callahan and McDonald 1992; McElroy et al. 2004). Preemergence herbicides also may injure juvenile turf (Fermanian et al. 2007).

Postemergence herbicide use is often warranted to control established annual bluegrass in turf. Postemergence control with herbicides can be hindered by a lengthy annual bluegrass germination period and multiple applications may be necessary (Beard et al. 1978; Kaminski and Dernoeden 2007; McElroy et al. 2004). Postemergence herbicides are used in late winter or spring to control annual bluegrass, but populations resistant to specific chemistries may limit potential for successful control. Annual bluegrass has developed resistance to several herbicide mechanisms of action. Resistance has been reported with inhibitors of 5-enolpyruvate shikimate-3-phosphate, acetolactate synthase, long chain fatty acid synthesis, mitosis, photosystem I, and photosystem II (Binkholder et al. 2011; Brosnan et al. 2012b; Cross et al. 2013; Cutulle et al. 2009; Harvey and Harper 1980; Heap 1997; Isrigg et al. 2002; Kelly et al. 1999; McElroy et al. 2013; Perry et al. 2012). Herbicides with these mechanisms of action have been repeatedly used due to cost effectiveness or tolerance of desirable turfgrasses.

Glyphosate is a nonselective herbicide that inhibits 5-enolpyruvylshikimate-3-phosphate synthase in the shikimic acid pathway (Amrhein 1980). Glyphosate is used for controlling annual bluegrass in dormant bermudagrass, but overuse has also resulted in the spread of resistant populations (Binkholder et al. 2011; Brosnan et al. 2012b). Acetolactate synthase inhibiting herbicides include bispyribac-sodium, imazaquin, and the sulfonylureas: flazasulfuron, foramsulfuron, and trifloxysulfuron. These herbicides inhibit acetolactate synthase, an enzyme in the biosynthesis of the branched-chain amino acids (LaRossa and Schloss 1984). Acetolactate synthase inhibiting herbicides are popular for postemergence annual bluegrass control in warm-season turfgrasses, but significant resistance issues have been reported (Cross et al. 2013; McElroy et al. 2013). Annual bluegrass biotypes have a history of developed resistance to bipyridyliums like paraquat that are photosystem I inhibitors (Fuerst and Vaughn 1990; Harvey and Harper 1980). Triazines (atrazine and simazine) are photosystem II inhibitors used for annual bluegrass control in warm-season turf. These herbicides inhibit photosynthesis by binding to D-1 proteins that transfer electrons from photosynthesis and cause highly reactive free radicals that damage cells (Devine et al. 1993). Free radicals oxidize and destroy membranes and pigments, resulting in cell death in susceptible species. Extensive use of triazines has led to prevalent annual bluegrass resistance (Darmency and Gasquez 1981; Kelly et al. 1999). There is also documented annual bluegrass resistance to other photosystem II inhibitors including amicarbazone, diuron, and metribuzin (Hanson and Mallory-Smith 2000; Mengistu et al. 2000; Perry et al. 2012).

Annual bluegrass resistance has resulted from repeated use of the same herbicide or mechanism of action over years. Utilizing herbicides with different mechanisms of action is necessary to combat resistance in long-term management. New herbicides and mechanisms of action could offer end-users alternatives for postemergence annual bluegrass control.

Flumioxazin

Flumioxazin (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione) is used in ornamentals, peanut (*Arachis hypogaea* L.), and soybean (*Glycine max* L.) for pre and postemergence weed control (Anonymous 2009a, Anonymous 2013; Grey and Wehtje 2005; Senseman 2007). In 2011, flumioxazin was labeled for pre and postemergence control in dormant bermudagrass (*Cynodon dactylon* (L.) Pers.) at use rates of 0.28 to 0.42 kg ai ha^{-1} (Anonymous 2011; Anonymous 2013). Flumioxazin causes rapid desiccation and necrosis of plant tissues when exposed to light and can provide residual weed control when applied to soil (Senseman 2007).

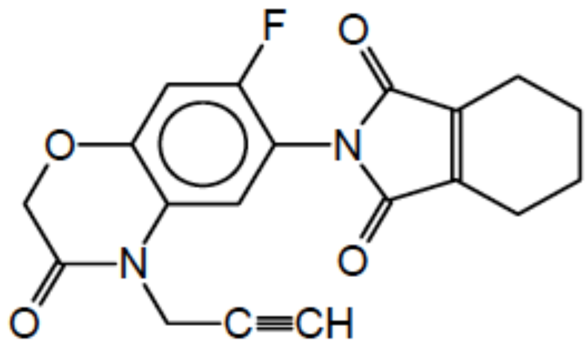

Figure 1.1. Flumioxazin chemical structure (Anonymous 2013).

Flumioxazin is a N-phenylphthalimide herbicide that inhibits protoporphyrinogen oxidase enzyme in susceptible weeds (Senseman 2007). Flumioxazin and other herbicides classified as Protox or PPO inhibitors inhibit the enzyme protoporphyrinogen oxidase (Protox, PPO) that catalyzes the conversion of protoporphyrinogen IX (Protogen IX) to protoporphyrin IX (Proto IX) as part of the tetrapyrrole biosynthesis pathway (Duke et al. 1991; Scalla and Matringe 1994). Tetrapyrroles, such as heme and chlorophyll, serve as cofactors in numerous essential enzymatic and signaling processes in plants including light harvesting, nitrogen fixation, oxygen transport, quenching of free radicals, respiration or phosphorylation, and storage (Beale and Weinstein 1990; Grimm 1999).

Susceptible species treated with a Protox inhibiting herbicide accumulate a substrate, Proto IX, that leads to cellular damage upon exposure to light (Becerril and Duke 1989; Scalla and Matringe 1994). Protox catalyzes Protogen IX to Proto IX is the cellular target for the herbicides that leads to the accumulation of Proto IX (Matringe et al. 1989; Witkowski and

Halling 1989). It is believed that as Protogen IX accumulates above normal levels, it diffuses out of the site of synthesis, and is oxidized nonenzymatically to Proto IX that is then no longer available to chelatases (Matringe et al. 1989). Protogen IX and Proto IX are specifically exported by plastids for transfer from chloroplasts for mitochondrial heme synthesis (Jacobs and Jacobs 1993). The export of the accumulating Protogen IX prevents feedback inhibition of the pathway.

The plasma membrane has the capability to oxidize Protogen IX to Proto IX through activity that differs from plastid and mitochondrial protox and does not respond to Protox inhibitor herbicides (Jacobs et al. 1991; Lee and Duke 1994). The lipophilicity of Proto IX is significantly greater than for Protogen IX and it is more likely to remain in membranes in which it is formed that accounts for destruction of plasma membranes (Duke et al. 1991; Duke et al. 1994). Proto IX in the presence of light and molecular oxygen generates high levels of singlet oxygen as an initiating factor for lipid peroxidation of polyunsaturated fatty acids in the plant membranes (Scalla and Matringe 1994). Singlet oxygen removes hydrogen from the fatty acids and form lipid radicals that react with oxygen forming peroxidized lipid radicals, which are able to propagate the reaction by extracting hydrogen from other polyunsaturated fatty acids (Scalla and Matringe 1994). This results in unstable lipid peroxides leading to degradation of the fatty acids and overall membrane integrity (Hess 2000).

The mechanism of action for Protox inhibitors is the inhibition of Protox, causing the accumulation of Proto IX that in the presence of light, leads to lipid peroxidation that results in cell death (Becerril and Duke 1989; Scalla and Matringe 1994). The herbicidal effects of Protox inhibitors are relatively quick due to fast build up of substrates rather than from the depletion of chlorophyll. The efficiency may also limit Protox inhibitors with their narrow selectivity.

Although flumioxazin is new to turfgrass, the herbicide has had extensive use for annual weed control in leguminous crops, cotton (*Gossypium hirsutum* L.), field corn (*Zea mays* L.), and ornamental species (Anonymous 2009a; Anonymous 2013; Grey and Wehtje 2005; Senseman 2007). Flumioxazin has potential for use in turfgrass and it may offer an alternative mechanism of action for postemergence annual bluegrass control. There is no documented annual bluegrass resistance to Protox inhibiting herbicides, and could effectively control biotypes resistant to other herbicide mechanisms of action.

Several Protox inhibiting herbicides are used in turfgrass including carfentrazone, oxadiazon, and sulfentrazone (Senseman 2007). Carfentrazone is a postemergence broadleaf herbicide that has short to no residual activity and is also used for silvery thread moss (*Bryum argenteum* Hedw.) control in turfgrass (Gillespie et al. 2011; Senseman 2007; Yelverton 2005). Carfentrazone is labeled for use in all major warm- and cool-season turfgrasses (Anonymous 2009b). Carfentrazone has rapid activity on weeds, but does not control perennials and has poor efficacy on annual bluegrass (Senseman 2007).

Oxadiazon controls many annual grassy weeds. Oxadiazon may be applied to newly established bermudagrass, zoysiagrass, and St. Augustinegrass (Senseman 2007). Oxadiazon effectively controls crabgrass (*Digitaria* spp.), goosegrass (*Eleusine indica* (L.) Gaertn.), and annual bluegrass with preemergence applications (Bingham and Shaver 1979; Johnson 1993; Senseman 2007). However, oxadiazon generally has no postemergence activity for controlling weeds and turf managers cannot apply sprayable formulations to actively growing grass (Anonymous 2007; Senseman 2007).

Sulfentrazone may be applied as a pre or postemergence treatment for controlling annual grasses, broadleaf weeds, and sedges (*Cyperus spp.*) (Blum et al. 2000; Brecke et al. 2005

Brosnan et al. 2012a). Sulfentrazone is labeled for use on most major warm- and cool-season turf, but may be phytotoxic in hot weather (Anonymous 2012; Senseman 2007). Sulfentrazone is often used in combination with pre or postemergence herbicides, but does not effectively control annual bluegrass.

Flumioxazin may control susceptible species with both pre and postemergence applications. Soil residual of flumioxazin may lead to root absorption and control of weed seedlings, such as crabgrass and goosegrass. In the Southern United States, flumioxazin applications are generally most effective for annual bluegrass control in November and December, and prior to annual bluegrass tillering (Flessner et al. 2013; McCullough et al. 2012). Applications at spring timings may control annual bluegrass with residual activity for controlling summer annual weeds, including goosegrass and crabgrass species: smooth (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) large (*Digitaria sanguinalis* (L.) Scop.), and southern (*Digitaria ciliaris* (Retz.) Koel.) (Anonymous 2013; McCullough et al. 2012). Although aspects of flumioxazin are advantageous, applications are limited to dormant bermudagrass due to injury on actively growing turf (Anonymous 2013; Umeda 2012).

Objective

Flumioxazin has potential to be an effective alternative mechanism of action for turfgrass managers, and could be the only herbicide for postemergence annual bluegrass control and residual summer annual weed control. However, there are considerable limitations on flumioxazin use, such as turf tolerance and limited efficacy during winter months. Comprehensive research is needed to evaluate flumioxazin use in various turfgrass species, and maximize efficacy for annual bluegrass control. The objectives of this research were to evaluate:

(1) effects of temperature and application placement on flumioxazin efficacy; (2) tolerance of five warm-season turf species to flumioxazin applied at various timings; (3) use of adjuvants on flumioxazin efficacy for annual bluegrass control; (4) tank-mixtures of flumioxazin with other herbicide mechanisms of action for postemergence annual bluegrass control.

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CHAPTER 2

TEMPERATURE AND APPLICATION PLACEMENT INFLUENCE FLUMIOXAZIN EFFICACY ON ANNUAL BLUEGRASS AND LARGE CRABGRASS[1]

[1]T. V. Reed, P. McCullough, and T. Grey. Submitted to *HortScience*, 10/25/13.

Abstract

Annual bluegrass (*Poa annua* L.) and large crabgrass (*Digitaria sanguinalis* (L.) Scop.) may reduce aesthetics and functionality of turfgrasses, and often warrant control with herbicides. Flumioxazin, a protoporphyrinogen oxidase inhibitor, offers an alternative mechanism of action for postemergence annual bluegrass control with residual control of crabgrass (*Digitaria* spp.) in turf. Research was conducted to evaluate the effects of air temperature and application placement on flumioxazin efficacy for annual bluegrass and large crabgrass control. Predicted rates for 50% injury (I_{50}) at 7 DAT (days after treatment) over six rates of flumioxazin, for annual bluegrass measured >3.36, 0.99, and 0.95 kg ai ha^{-1} at 10, 20, 30° C, respectively, while large crabgrass measured >3.36, 1.36, and 0.73 kg ha^{-1}, respectively. At 28 DAT, annual bluegrass injury ranged 38 to 77%, 51 to 79%, and 43 to 82%, at 10, 20, and 30° C, respectively, while large crabgrass injury ranged 52 to 81%, 43 to 84%, and 56 to 89%, at 10, 20, and 30° C, respectively. At 28 DAT, SR_{50} values (50% dry shoot weight reductions from the nontreated) measured <0.30 kg ha^{-1} for annual bluegrass and large crabgrass at all temperatures. In the application placement experiment, annual bluegrass and large crabgrass injury ranged 78 to 83% from soil-only and soil-plus-foliar flumioxazin treatments at 0.42 and 0.84 kg ha^{-1} at 28 DAT. Foliar-only applications of flumioxazin caused ≤58% injury to both species. Overall, annual bluegrass and large crabgrass injury from flumioxazin increased with temperature from 10 to 30° C, while soil-only and soil-plus-foliar applications resulted in greater control of both species than foliar-only treatments.

Introduction

Annual bluegrass (*Poa annua* L.) is a problematic winter annual weed in turfgrasses (Beard 1970; Beard et al. 1978; Vargas 1996). Annual bluegrass has a bunch-type growth habit, light green color, and abundant seedhead production that may compromise turf aesthetics and functionality (Beard et al. 1978; Lush 1989; Vargas 1996). As annual bluegrass declines with warmer temperatures, summer annual species, for example, large crabgrass (*Digitaria sanguinalis* (L.) Scop.) may emerge in the voids, further reducing turf quality (Johnson 1996; Tae-Joon et al. 2002).

Flumioxazin, a protoporphyrinogen oxidase (Protox) inhibitor, offers an alternative mechanism of action to current herbicides for postemergence (POST) annual bluegrass control in turf (Flessner et al. 2013). Flumioxazin spring applications may also provide preemergence (PRE) control of smooth crabgrass (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) and other annual weeds (McCullough et al. 2012). The enzyme, Protox, catalyzes the conversion of protoporphyrinogen IX (Protogen IX) to protoporphyrin IX (Proto IX) as part of the tetrapyrrole biosynthesis pathway (Duke et al. 1991; Scalla and Matringe 1994). Tetrapyrroles, such as chlorophyll, serve as cofactors in numerous essential enzymatic and signaling processes in plants (Beale and Weinstein, 1990; Grimm 1999). Protox inhibition causes the accumulation of Proto IX that, in the presence of light, leads to lipid peroxidation and loss of membrane integrity (Becerril and Duke 1989; Scalla and Matringe 1994). In susceptible species, flumioxazin foliar treatments cause rapid desiccation and necrosis of exposed plant tissues, and soil applications control emerging plants (Senseman 2007).

Annual bluegrass susceptibility to flumioxazin varies with application timing, and may be affected by environmental conditions such as temperature (Flessner et al. 2013; McCullough et al. 2012). Previous research indicated annual bluegrass and large crabgrass susceptibility to POST herbicides was influenced by temperature. For example, amicarbazone and bispyribac-sodium applications caused greater annual bluegrass phytotoxicity as temperature increased from 10 to 30° C (McCullough and Hart 2006; McCullough et al. 2010). POST herbicide efficacy also increases with temperature for atrazine, glyphosate, and sulfosulfuron (Al-Khatib et al. 1992; McWhorter 1980; Olson et al. 2000). Efficacy of Protox inhibiting herbicides, such as flumiclorac and fluthiacet, increases with temperature on redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) (Fausey and Renner 2001). Since flumioxazin is applied during winter months in turf, temperature may be an influential factor for successful applications in turfgrass.

Application placement has shown to affect herbicide efficacy for POST control of annual grassy weeds. For example, Brosnan and Breeden (2012) noted ≥86 and 90% control of annual bluegrass and smooth crabgrass, respectively, with soil-only and soil-plus-foliar applications of indaziflam by 28 days after treatment (DAT). Foliar-only applications of indaziflam provided <30% control of both species. Perry et al. (2011) observed greater annual bluegrass control with soil-only and soil-plus-foliar applications of amicarbazone compared to applications made only to foliage. McCurdy et al. (2009) reported that greatest control of large crabgrass from mesotrione was soil-plus-foliar application at 28 DAT. Similar results were noted with sulfentrazone, a Protox inhibitor, as yellow nutsedge (*Cyperus esculentus* L.), purple nutsedge (*Cyperus rotundus* L.), and false green kyllinga (*Kyllinga gracillima* Miq.) were less susceptible to foliar-only applications than soil applications (Gannon et al. 2012).

The registration of flumioxazin in turfgrass has important implications for PRE and POST weed control. Flumioxazin could provide an alternative mechanism of action for POST annual bluegrass control, and reduce the use of other herbicides for PRE crabgrass control in spring. However, comprehensive investigations are required to evaluate application parameters that influence flumioxazin efficacy. The objective of this research was to evaluate effects of temperature and application placement on flumioxazin efficacy for annual bluegrass and large crabgrass control.

Materials and Methods

Temperature Experiment. Growth chamber experiments were conducted in Griffin, GA (33.26°N, 84.28°W) to investigate the effect of air temperature on annual bluegrass and large crabgrass response to flumioxazin. The two species were planted in a 80:20 (v:v) mixture of a coarse textured sand and peat moss in 12.6 cm^2 surface area x 20.5 cm depth plastic pots in a greenhouse set for 23/15° C and 32/25° C (day/night) temperature for annual bluegrass and large crabgrass, respectively. Pots were thinned to one multi-leaf (4-5) plant before application. Grasses were acclimated to temperatures of 10, 20, or 30° C with a 12 hour photoperiod and approximately 80% relative humidity, for 48 hours prior to application. Flumioxazin (SureGuard® 51WG, Valent U.S.A. Corporation, Walnut Creek, CA) was applied at 0, 0.105, 0.21, 0.42, 0.84, 1.68, and 3.36 kg ai ha^{-1} with 0.25% v/v nonionic surfactant (Chem Nut 80-20. Chem Nut Inc., Albany, GA). Herbicide treatments were applied with a CO_2-pressured backpack sprayer calibrated to deliver 374 L ha^{-1} with a single 9504E flat-fan nozzle (Tee Jet, Spraying Systems Co., Roswell, GA). Irrigation was withheld for 24 hours after application and then pots were watered as needed to prevent soil moisture deficiencies.

The experiment was a split-plot design with four replications and was repeated. Due to limitations of available chambers, only one chamber was used for each temperature. Injury was evaluated at 4, 7, 14, and 28 DAT on a 0 to 100 percent scale where 0 equals no visible chlorosis or stunting and 100 equals complete desiccation. Plant shoots were harvested at soil surface 28 DAT, oven-dried at 60° C for 48 hours, and then weighed. Shoot biomass was converted to percent reduction of the nontreated. Data were subjected to analysis of variance in SAS (SAS® Institute v. 9.3, Cary, NC). Predicted rates of flumioxazin that provided 50% injury (I_{50}) and 50% dry shoot weight reductions from the nontreated (SR_{50}) were determined with nonlinear regression analysis using SigmaPlot (Systat Software Inc. SigmaPlot v. 11.0, San Jose, CA), with polynomial, quadratic equation: $y = a + bx + cx^2$ where *y* is relative injury or shoot mass reductions from the nontreated expressed as a percentage, *a*, *b*, and *c* are constants, and *x* is rate of flumioxazin. Means of predicted I_{50} and SR_{50} values were separated using Fisher's Protected LSD Test at $\alpha = 0.05$. Experiment by treatment interactions were not detected, and thus experiments were combined. Species were analyzed separately.

Application Placement Experiment. Greenhouse studies were conducted in Griffin, GA (33.26°N, 84.28°W), from June to August 2012, to investigate application placement of flumioxazin on annual bluegrass and large crabgrass control using methods similar to previous research (Lycan and Hart 2006; McElroy et al. 2004; Wehtje and Walker 2002; Williams et al. 2003). The two species were planted in a 80:20 (v:v) mixture of a coarse textured sand and peat moss in 79.0 cm^2 surface area x 8.9 cm depth plastic pots in a greenhouse set for 23/15° C and 32/25° C (day/night) temperature for annual bluegrass and large crabgrass, respectively. Pots were thinned to one multi-leaf (4-5) plant before application. Application placements included: soil-only, foliar-only, and foliar-plus-soil. Flumioxazin (SureGuard® 51WG, Valent U.S.A. Corporation, Walnut Creek, CA) was applied at 0, 0.21, 0.42, and 0.84 kg ai ha^{-1} with 0.25% v/v nonionic surfactant (Chem Nut 80-20, Chem Nut Inc., Albany, GA) for each of the placements. Foliar-only and foliar-plus-soil treatments were applied with a CO_2-pressured backpack sprayer calibrated to deliver 374 L ha^{-1} with a single 9504E flat-fan nozzle (Tee Jet, Spraying Systems Co., Roswell, GA). Prior to application, a 1 cm layer of activated charcoal (AQUA-Tech® Activated Carbon, United Pet Group, Inc. Cincinnati, OH) was placed on soil surface of pots receiving foliar-only treatments. The activated charcoal was removed within four hours after applications. Soil-only treatments were applied in 10 ml with a syringe to the surface area of the pots. All pots were kept in a greenhouse with a 23/15° C (day/night) temperature and irrigation was withheld for 24 hours then watered as needed. Large crabgrass was acclimated to 23/15° C (day/night) temperature for 48 hours prior to treatment. Experimental design was a randomized complete block with four replications and was repeated. Injury was evaluated at 7, 14, 21, and 28 DAT on a 0 to 100 percent scale where 0 equals no visible chlorosis or stunting and 100 equals complete desiccation. Plant shoots were harvested at soil surface at 28 DAT, oven-dried at 60° C for 48 hours, and then weighed. Shoot biomass was converted to percent reduction of the nontreated by replication.

Data were subjected to analysis of variance at the 0.05 probability level in SAS. Orthogonal polynomial contrasts were used to evaluate relationship of plant response with flumioxazin rate. Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$. Experiment by treatment interactions were not detected and, thus, experiments were combined. Species were analyzed separately.

Results and Discussion

Temperature Experiment. Temperature by rate interaction was detected for injury and shoot mass, and thus, temperatures are presented separately. Flumioxazin caused greater injury at 4 DAT to annual bluegrass and large crabgrass as temperatures increased from 10 to 30° C (Figure 2.1). At 7 DAT, annual bluegrass injury ranged 16 to 37%, 21 to 61%, and 20 to 67%, at 10, 20, and 30° C respectively, while large crabgrass injury ranged 14 to 35%, 23 to 52%, and 32 to 76% respectively. At 7 DAT, I_{50} values for annual bluegrass were >3.36, 0.99, and 0.95 kg ha^{-1} at 10, 20, 30° C, respectively, while large crabgrass were >3.36, 1.36, and 0.73 kg ha^{-1}, respectively (Table 2.1). Flumioxazin efficacy increasing at warmer temperatures is consistent with previous research with other Protox inhibiting herbicides on common lambsquarters and redroot pigweed (Fausey and Renner 2001). Increased efficacy at warmer temperatures is also similar to research with other POST annual bluegrass herbicides, including amicarbazone, atrazine, bispyribac-sodium, and glyphosate (Al-Khatib et al. 1992; McCullough and Hart 2006; McCullough et al. 2010; McWhorter 1980; McWhorter and Azlin 1978).

Temperature effects on flumioxazin efficacy diminished at 14 and 28 DAT, and grasses had comparable injury across temperatures. At 14 DAT, injury of annual bluegrass ranged 28 to 66%, 33 to 70%, and 29 to 73%, at 10, 20, and 30° C, respectively. At 28 DAT large crabgrass injury ranged 52 to 81%, 43 to 84%, and 56 to 89%, at 10, 20, and 30° C, respectively. At 28 DAT, I_{50} values were 0.17, <0.105, and <0.105 kg ha^{-1} at 10, 20, 30° C, respectively, while large crabgrass was <0.105 kg ha^{-1} at all temperatures. At 28 DAT, SR_{50} values measured <0.105 kg ha^{-1} for annual bluegrass and large crabgrass at all temperatures, except annual bluegrass at 30° C which was 0.27 kg ai ha^{-1} (Figure 2.2). Reduced efficacy of low flumioxazin rates on annual bluegrass at warmer temperature probably resulted from less growth of the nontreated in these conditions.

Annual bluegrass has been previously reported to be more susceptible to herbicides at warmer temperatures. McCullough and Hart (2006) noted that as temperatures increased from 10 to 30° C, bispyribac-sodium rates required for 50% leaf chlorosis decreased from >0.296 to 0.098 kg ha^{-1} and rates required to achieve 50% clipping reduction decreased from 0.085 to 0.031 kg ha^{-1}. However, Johnson and Young (2002) noted large crabgrass was more susceptible to mesotrione at 18° C than 32° C. The researchers surmised that large crabgrass has more active growth at warmer temperatures, but susceptibility increases with cooler temperatures due to less metabolism. Tolerant plants, such as soybeans and peanuts, are believed to rapidly metabolize flumioxazin (Senseman 2007). Increased temperatures also have been associated with increased absorption and translocation of fenoxaprop, picloram, and triclopyr that may increase herbicide efficacy (Radosevich and Bayer 1979; Xie et al. 1996). Overall, flumioxazin caused more rapid injury to annual bluegrass and large crabgrass as temperatures increased from 10 to 30° C.

Application Placement Experiment. Rate by placement interactions were detected for annual bluegrass and large crabgrass, and thus, all combinations are presented. Soil-only and soil-plus-foliar applications of flumioxazin caused greater injury to annual bluegrass and large crabgrass than foliar-only applications on all dates evaluated (Table 2.2). Injury from soil-only and soil-plus-foliar applications of flumioxazin ranged 34 to 49% and 47 to 64% for annual bluegrass and large crabgrass, respectively, at 7 DAT. Injury from foliar-only applications ranged 22 to 39% for both species, and linearly increased with rate. Flumioxazin at 0.42 and 0.84 kg ai ha^{-1} caused similar injury from soil-only and soil-plus-foliar treatments from 7 to 28 DAT to both species.

Annual bluegrass and large crabgrass injury ranged 78 to 83% from these applications at 28 DAT, and injury was comparable across rates of soil-only treatments. Foliar-only applications of flumioxazin at all rates caused ≤58% injury to both species.

Rate by placement interactions were not detected for annual bluegrass and large crabgrass shoot mass reductions from the nontreated, and thus, results are presented by main effects. At 28 DAT, shoot mass was reduced ≥57% and ≥68% from nontreated annual bluegrass and large crabgrass, respectively (Table 2.3). Shoot mass reductions of annual bluegrass and large crabgrass linearly increased with rate, regardless of application placement. Annual bluegrass shoot mass reductions from soil-only and soil-plus-foliar applications were 72% and 69%, respectively, while foliar-only treatments were 58% from nontreated. Large crabgrass had ≥ 80% shoot mass reductions from flumioxazin soil-only and soil-plus-foliar applications, but all large crabgrass biomass was reduced >65%.

Greater efficacy of Protox inhibiting herbicides with soil-only and soil-plus foliar applications, compared to foliar-only treatments, concurs with previous research by Gannon et al. (2012) with sulfentrazone. Similar results were noted on annual bluegrass with soil-only and soil-plus-foliar applications of amicarbazone and indaziflam to annual bluegrass (Brosnan and Breeden 2012; Perry et al. 2011). Lycan and Hart (2006) also reported soil-only and soil-plus-foliar applications of bispyribac-sodium at 0.148 and 0.296 kg ha^{-1} resulted in greater injury and shoot dry weight reduction of annual bluegrass at 28 DAT than foliar-only treatments. McCurdy et al. (2009) reported that soil applied mesotrione treatments provided the greatest control of large crabgrass and reduced foliar dry weight more effectively than foliar-only treatments.

Conclusion

Temperature and application placement affect flumioxazin efficacy for annual bluegrass and large crabgrass control. Flumioxazin caused greater injury to annual bluegrass and large crabgrass as temperatures increased from 10 to 30° C. Practitioners may fail to control annual bluegrass during winter months due to less injury following flumioxazin treatments compared to late fall timings. Soil-only and soil-plus-foliar applications of flumioxazin resulted in greater control of both species than foliar-only applied treatments. Results suggest root uptake is critical for maximizing flumioxazin efficacy for annual bluegrass and large crabgrass control in turfgrass. Further research is needed to evaluate methods for enhancing flumioxazin efficacy during winter months. Perhaps adjuvants could increase foliar penetration to improve POST annual bluegrass control during winter months, but further investigation is warranted in turfgrass.

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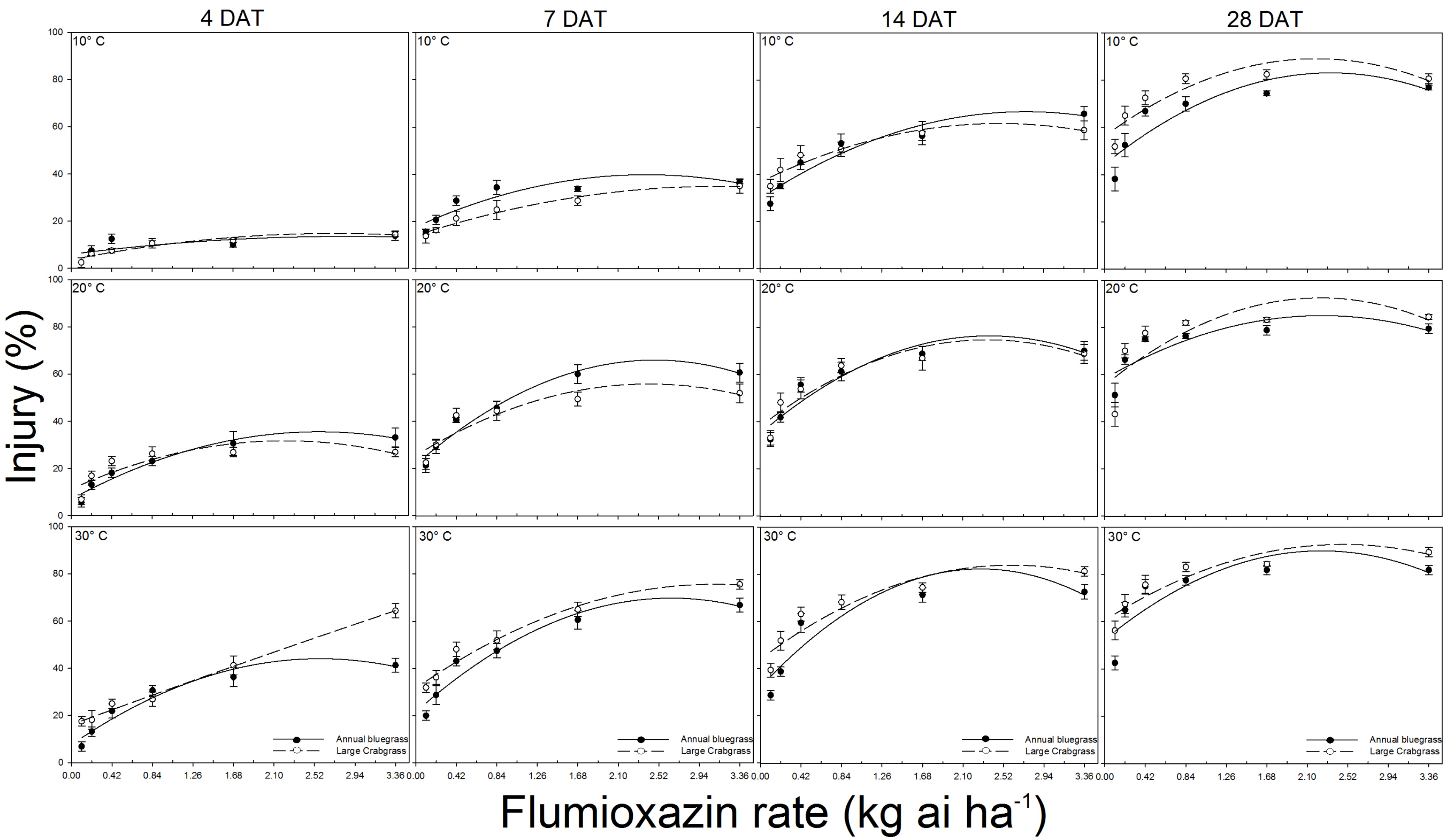

Figure 2.1. Injury of annual bluegrass and large crabgrass following flumioxazin applications in two combined growth chamber experiments, 2012, Griffin, GA. Error bars represent standard error of the mean. Nonlinear regression equations are listed in Table 2.1. Abbreviation, DAT: days after treatment.

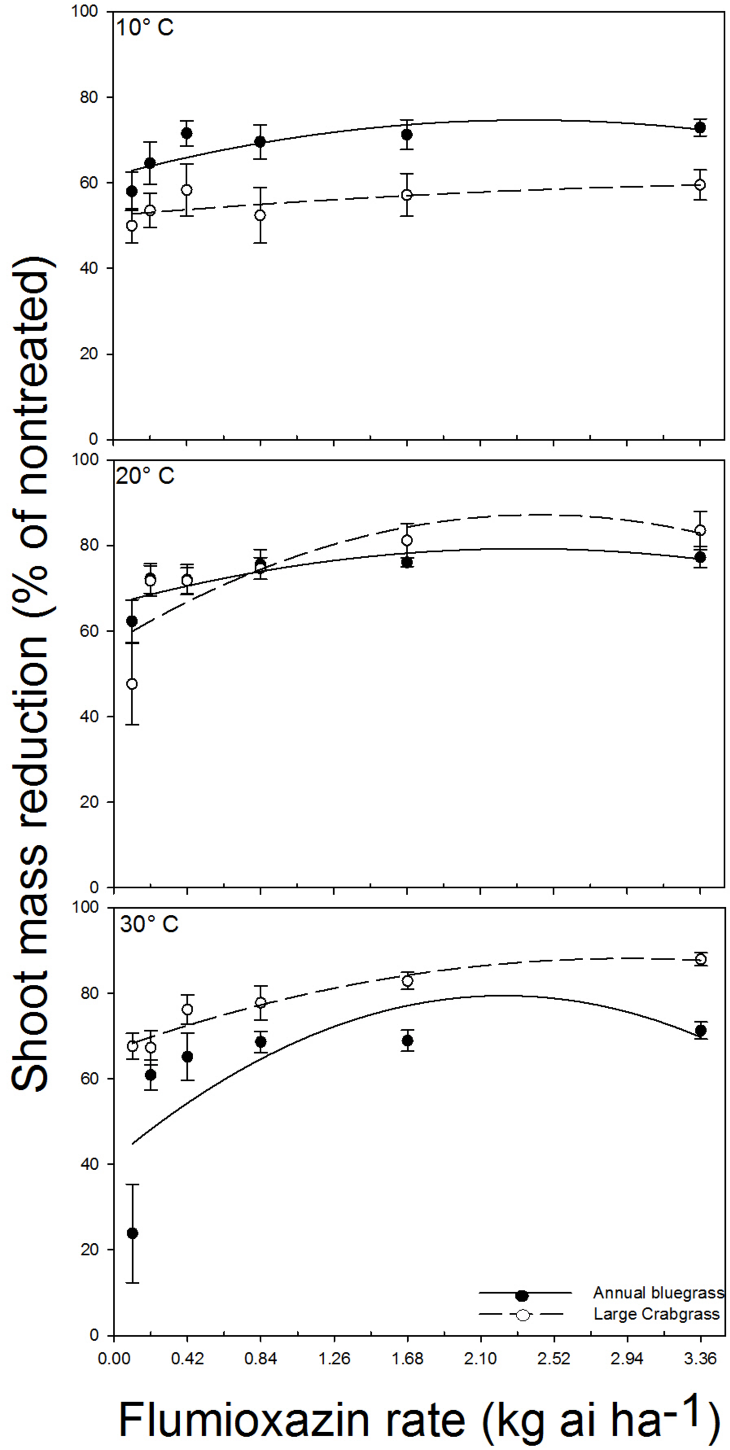

Figure 2.2. Shoot mass reductions of annual bluegrass and large crabgrass 28 DAT from flumioxazin applications in two combined growth chamber experiments, 2012, Griffin, GA. Error bars represent standard error of the mean. Nonlinear regression equations are listed in Table 2.1. Abbreviation, DAT: days after treatment.

Table 2.1. Predicted rates (kg ai ha^{-1}) of flumioxazin required to provide 50% injury (I_{50}) and 50% shoot mass reductions (SR_{50}) of annual bluegrass and large crabgrass in two combined growth chamber experiments, 2012, Griffin, GA.

		I_{50} (DAT[a])				SR_{50} (DAT)
Species	Temperature (°C)	4	7	14	28	28
		kg ai ha^{-1}				
Annual bluegrass	10	>3.36	>3.36	0.91	0.17	<0.105
	20	>3.36	0.99	0.48	<0.105	<0.105
	30	>3.36	0.95	0.45	<0.105	0.27
Large crabgrass	10	>3.36	>3.36	0.79	<0.105	<0.105
	20	>3.36	1.36	0.42	<0.105	<0.105
	30	2.32	0.73	0.20	<0.105	<0.105
	$LSD_{0.05}$	0.40	0.58	0.38	0.06	0.31
		Equations[c]				
Annual bluegrass	10	$y = 5.97 + 5.27x - 0.92x^2$ $r^2 = 0.21$; SE[b] = 5.16	$y = 17.61 + 18.53x - 3.87x^2$ $r^2 = 0.60$; SE = 5.97	$y = 29.84 + 26.63x - 4.83x^2$ $r^2 = 0.66$; SE = 9.17	$y = 44.38 + 33.05x - 7.05x^2$ $r^2 = 0.55$; SE = 11.23	$y = 61.75 + 10.89x - 2.29x^2$ $r^2 = 0.62$; SE[b] = 4.52
	20	$y = 6.95 + 22.25x - 4.33x^2$ $r^2 = 0.56$; SE =8.48	$y = 21.58 + 35.75x - 7.21x^2$ $r^2 = 0.74$; SE = 8.82	$y = 34.99 + 34.83x - 7.33x^2$ $r^2 = 0.67$; SE = 9.47	$y = 58.19 + 23.70x - 5.26x^2$ $r^2 = 0.49$; SE = 8.68	$y = 66.33 + 11.02x - 2.35x^2$ $r^2 = 0.66$; SE = 4.09
	30	$y = 7.57 + 28.31x - 5.49x^2$ $r^2 = 0.71$; SE = 7.90	$y = 21.57 + 36.42x - 6.87x^2$ $r^2 = 74$; SE = 9.64	$y = 32.21 + 43.81x - 9.59x^2$ $r^2 = 0.61$; SE = 10.74	$y = 52.41 + 33.47x - 7.45x^2$ $r^2 = 0.57$; SE = 10.42	$y = 41.32 + 34.14x - 7.65x^2$ $r^2 = 0.50$; SE = 16.37
Large crabgrass	10	$y = 3.96 + 7.47x - 1.33x^2$ $r^2 = 0.42$; SE = 4.26	$y = 14.00 + 13.29x - 2.12x^2$ $r^2 = 0.65$; SE = 5.36	$y = 36.69 + 20.01x - 4.03x^2$ $r^2 = 0.36$; SE = 11.06	$y = 56.35 + 29.89x - 6.82x^2$ $r^2 = 0.58$; SE = 8.70	$y = 52.36 + 3.41x - 0.39x^2$ $r^2 = 0.49$; SE = 3.44
	20	$y = 11.24 + 18.50x - 4.18x^2$ $r^2 = 0.43$; SE = 7.32	$y = 25.46 + 25.09x - 5.19x^2$ $r^2 = 0.46$; SE = 10.91	$y = 37.96 + 31.23x - 6.64x^2$ $r^2 = 0.63$; SE = 9.06	$y = 55.39 + 33.16x - 7.42x^2$ $r^2 = 0.48$; SE = 12.23	$y = 57.40 + 24.47x - 5.03x^2$ $r^2 = 0.66$; SE = 9.57
	30	$y = 16.09 + 15.06x - 0.20x^2$ $r^2 = 0.80$; SE = 8.36	$y = 31.62 + 28.47x - 4.60x^2$ $r^2 = 0.76$; SE = 8.78	$y = 44.02 + 30.68x - 5.91x^2$ $r^2 = 0.67$; SE = 9.39	$y = 60.93+ 25.35x - 5.12x^2$ $r^2 = 0.53$; SE = 9.83	$y = 66.81 + 14.51x - 2.47x^2$ $r^2 = 0.93$; SE = 2.74

[a]DAT = days after treatment.

[b]SE = standard errors of the estimate.

[c]Nonlinear regression analysis using polynomial, quadratic equation: $y = a + bx + cx^2$ where y is relative injury or shoot mass reduction from the nontreated expressed as a percentage, a, b, and c are constants, and x is rate of flumioxazin.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$.

LSD = least significant difference.

Table 2.2. Annual bluegrass and large crabgrass injury from flumioxazin applications in two combined greenhouse experiments, 2012-2013, Griffin, GA.

			Injury (DAT[a])							
			Annual bluegrass				Large crabgrass			
Placement	Rate		7	14	21	28	7	14	21	28
	kg ai ha^{-1}		%							
Foliar	0.21		22	26	32	32	22	31	35	31
	0.42		28	36	49	53	35	45	54	58
	0.84		29	36	46	49	39	45	54	57
Soil	0.21		43	59	70	76	47	68	73	78
	0.42		44	59	70	79	54	70	76	81
	0.84		45	64	73	79	63	71	76	82
Soil+Foliar	0.21		34	47	58	61	48	53	61	64
	0.42		41	56	70	78	59	72	77	81
	0.84		49	63	74	83	64	73	77	81
	$LSD_{0.05}$		7	10	14	13	9	10	11	11
	Placement		*	*	*	*	*	*	*	*
	Rate		*	*	*	*	*	*	*	*
		Linear		*		*	*			
		Quadratic		NS		*	NS			
	Placement*Rate		*	NS	*	NS	NS	*	*	*
Foliar	Rate	Linear	*		*			*	*	*
		Quadratic	NS		*			NS	NS	*
Soil	Rate	Linear	NS		NS			NS	*	*
		Quadratic	NS		NS			NS	NS	NS
Soil+Foliar	Rate	Linear	*		*			*	*	*
		Quadratic	NS		NS			*	*	*

[a]DAT = days after treatment.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of plant response with flumioxazin rate.

LSD = least significant difference; * = significant; NS = not significant.

Table 2.3. Annual bluegrass and large crabgrass shoot mass reductions from flumioxazin applications in two combined greenhouse experiments, 2012-2013, Griffin, GA.

	Shoot Mass Reduction (28 DAT[a])	
Placement	Annual bluegrass	Large crabgrass
	------------------------ % ------------------------	
Foliar	58	68
Soil	72	80
Soil+Foliar	69	83
$LSD_{0.05}$	11	12
Rate (kg ai ha^{-1})		
0.21	57	68
0.42	63	79
0.84	78	83
$LSD_{0.05}$	11	12
Placement	*	*
Rate	*	*
Linear	*	*
Quadratic	NS	NS
Placement*Rate	NS	NS

[a]DAT = days after treatment.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of plant response with flumioxazin rate.

LSD = least significant difference; * = significant; NS = not significant.

CHAPTER 3

TOLERANCE OF FIVE WARM-SEASON TURFGRASS SPECIES TO FLUMIOXAZIN[2]

[2] T. V. Reed and P. McCullough. Accepted by *Weed Technology*.
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Abstract

Flumioxazin provides pre- and postemergence annual weed control in dormant bermudagrass (*Cynodon dactylon* (L.) Pers.), but applications during active growth may be injurious. Flumioxazin could also provide an alternative chemistry for postemergence annual bluegrass control in other turfgrasses, but research is limited on tolerance levels. The objective of this research was to evaluate tolerance of five warm-season turfgrasses to flumioxazin applied at various rates and timings. Late winter applications at 0.21, 0.42, or 0.84 kg ai ha^{-1} caused acceptable (<20%) injury to bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass at 3, 6, and 9 weeks after treatment (WAT) in both years. In 2012, late winter applications to centipedegrass caused unacceptable injury at 6 WAT, but turf recovered to acceptable levels by 9 WAT at all rates. Applications made during active turfgrass growth caused unacceptable initial injury to all species. However, bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass recovered to <20% injury by 9 WAT from all rates. In 2012, centipedegrass treated in mid-spring had 0, 24, and 74% injury from 0.21, 0.42, and 0.84 kg ai ha^{-1}, respectively at 9 WAT. In 2013, mid-spring applications to centipedegrass caused 13, 48, and 71% injury from 0.21, 0.42, and 0.84 kg ai ha^{-1}, respectively at 9 WAT. Overall, flumioxazin may be applicable for controlling annual weeds in bermudagrass, seashore paspalum, St. Augustinegrass and zoysiagrass with late winter applications before greenup, but all turfgrasses may be excessively injured during active growth.

Introduction

Annual bluegrass (*Poa annua* L.) is a problematic winter annual weed in turfgrass. Annual bluegrass has a bunch-type growth habit, light green color, and abundant seedhead production (Beard et al. 1978; Lush 1989; Vargas 1996). Postemergence (POST) herbicides are often used to control established annual bluegrass in turf. However, annual bluegrass has developed resistance to several herbicide chemistries including glyphosate, sulfonylureas, and triazines (Brosnan et al. 2012b; Heap 1997; Kelly et al. 1999; McElroy et al. 2013). Thus, herbicides with different mechanisms of action are necessary for POST annual bluegrass control in turfgrass management.

Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor that may offer an alternative mechanism of action for POST annual bluegrass control in turf (Flessner et al. 2013). Protox inhibition from herbicides, such as flumioxazin, causes the accumulation of Proto IX that leads to lipid peroxidation and loss of membrane integrity (Becerril and Duke 1989; Duke et al. 1991; Scalla and Matringe 1994). Flumioxazin is currently used for pre- and postemergence weed control in ornamentals, peanut (*Arachis hypogaea* L.), soybean (*Glycine max* L.), and other crops, but research is limited in turfgrass (Grey and Wehtje 2005; Senseman 2007).

Warm-season turfgrasses are tolerant to several Protox inhibiting herbicides. For example, oxadiazon is a preemergence (PRE) herbicide applied for controlling grassy and broadleaf weeds in turfgrass (Johnson 1997; McCarty and Weinbrecht 1997; Senseman 2007). Oxadiazon may be safely applied to bermudagrass, seashore paspalum, and zoysiagrass before, during, and after establishment (Brecke et al. 2010). However, turf managers are limited to granular formulations of oxadiazon on warm-season turfgrasses after greenup due to excessive injury caused by sprayable formulations (Johnson 1976; Johnson and Carrow 1999; Patton et al. 2007). Sulfentrazone is another Protox inhibitor that is applied for PRE or POST control of sedges, broadleaf weeds, and select grassy weeds in warm- and cool-season turfgrasses (Blum et al. 2000; Brecke et al. 2005; Brosnan et al. 2012a; McCullough et al. 2012b). Carfentrazone is a

POST herbicide that is used for controlling mosses and broadleaf weeds, and is generally safe on all major warm- and cool-season turfgrasses (Senseman 2007; Yelverton 2005). However, none of these herbicides provide POST annual bluegrass control.

Flumioxazin is the only Protox inhibitor labeled in turfgrass with selectivity for POST control of annual bluegrass, and may offer end-users an alternative mechanism of action from other herbicides (Flessner et al. 2013; McCullough et al. 2012a). Flumioxazin is currently only labeled for dormant bermudagrass due to injury concerns during active growth (Anonymous 2011; Umeda 2012). Applications may have potential for use in other warm-season grasses, but comprehensive research on turfgrass tolerance to flumioxazin is limited. The objective of this research was to evaluate tolerance of five warm-season turfgrasses to application timing and rate of flumioxazin.

Materials and Methods

Field experiments were conducted in Griffin, GA (33.26°N, 84.28°W), from February to June in 2012 and 2013. Soil was a Cecil sandy clay loam soil (fine, kaolinitic, thermic Typic Kanhapludults) with 2.5% organic matter and a pH of 6.0. Species evaluated included 'Tifway' bermudagrass, 'TifBlair' centipedegrass, 'Sea Isle I' seashore paspalum, 'Palmetto' St. Augustinegrass, and 'Zeon' zoysiagrass mowed at 1.6, 5, 1.6, 7, and 5 cm height, respectively. Bermudagrass and seashore paspalum were mowed during active growth with reel-mowers two and three days per week, respectively, while centipedegrass, St. Augustinegrass, and zoysiagrass were mowed weekly with rotary mowers. All fields had clippings returned and were irrigated as needed to prevent turf wilting.

Treatments were the factorial combination of three flumioxazin rates and three application timings. Flumioxazin (SureGuard® 51WG, Valent U.S.A. Corporation, Walnut Creek, CA) was applied at 0.21, 0.42, or 0.84 kg ai ha^{-1}. Treatments included a nonionic surfactant at 0.25% v/v (Chem Nut 80-20. Chem Nut Inc., Albany, GA). Application timings included late winter, preemergence (PRE) crabgrass timing, or mid-spring. Applications were made February 2, March 16, or April 27 in 2012 and February 1, March 14, or April 26 in 2013. Herbicide treatments were applied with a CO_2-pressured backpack sprayer calibrated to deliver 374 L ha^{-1} with a single 9504E flat-fan nozzle (Tee Jet, Spraying Systems Co., Roswell, GA).

Experimental design was a randomized complete block with four replications of 1 x 3 m plots on each field. Injury was visually measured on a percent scale where 0 equaled no injury and 100 equaled completely dead turf. Visual ratings were taken 1, 3, 6, and 9 weeks after treatment (WAT), except for 1 WAT for late winter applications due to dormancy of turfgrasses. On days of application, green cover of the nontreated was visually rated on a percent scale where 0 equaled completely dormant, brown turf and 100 equaled completely green turf. Green cover in grid counts were taken June 29, 2012 and June 28, 2013 and presented as a percent reduction from the nontreated. The sampling grid was 0.58 m^2 with 36 grids measuring 12.7 x 12.7 cm, and green cover was measured by counting the number of squares per plot with injured turfgrass. Data were subjected to analysis of variance at the 0.05 probability level. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate. Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$. Year by treatment interactions were detected and, thus, years are presented independently. Species were analyzed separately. Rate by timing interactions were detected, and thus, all combinations are presented.

Results and Discussion

Bermudagrass. In 2012, bermudagrass had 4% (±1), 46% (±3), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively (Table 3.1). In 2013, bermudagrass had 0% (±0), 2% (±1), 100% (±0) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. Flumioxazin late winter applications to bermudagrass caused acceptable (<20%) injury. PRE crabgrass applications in 2012, and mid-spring treatments in both years, caused >35% injury at 1 WAT. In 2012, bermudagrass injury linearly increased with rate from PRE crabgrass and mid-spring timings at 3 WAT. In 2012, only PRE crabgrass applications of flumioxazin at 0.42 and 0.84 kg ai ha^{-1} caused injury ≥20% at 3 WAT. In 2013, only the mid-spring application at 0.84 kg ai ha^{-1} caused injury ≥20% at 3 WAT. At 6 WAT, bermudagrass was injured ≤10% at all application timings of flumioxazin in both years, and no treatment reduced bermudagrass green cover in late June.

Green cover of all turfgrasses was variable between years due to cooler temperatures in 2013 than in 2012 during early months of the experiment (Figure 3.1). In 2013, cooler temperatures resulted in delayed turfgrass greenup that may have reduced injury from late winter and PRE crabgrass timings. Efficacy of Protox inhibiting herbicides has also shown to be affected by temperature. For example, flumiclorac and fluthiacet reduced control of redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) as temperature decreased from 40 to 10° C (Fausey and Renner 2001). When soil temperatures are <10° C, warm-season turfgrasses cease growth that may decrease susceptibility to herbicides due to less green leaf tissue, photosynthesis, and absorption (Fidanza and Johnson 2001; Patton and Reicher 2007; White and Schmidt 1989; Youngner 1959).

Bermudagrass tolerance to Protox inhibitors has been reported, but flumioxazin has received limited investigation. Oxadiazon may be applied at late winter and PRE crabgrass timings without injuring or reducing bermudagrass growth. Johnson (1976) noted February and March applications of granular oxadiazon at 3.4 and 4.5 kg ha^{-1} did not affect bermudagrass quality or density. Other Protox inhibitors may be safely applied to actively growing bermudagrass. For example, McCullough et al. (2012b) noted sulfentrazone applications to actively growing bermudagrass caused <20% injury. Brosnan et al. (2012a) reported summer applications of carfentrazone or sulfentrazone mixed with metsulfuron caused <10% injury to bermudagrass. Flessner et al. (2013) noted November flumioxazin treatments at 0.21 and 0.43 kg ha^{-1} to 100% green cover bermudagrass resulted in 46 and 52% necrosis, respectively, at 8 days after treatment (DAT). The applications induced early dormancy with no adverse affects on following spring greenup. Bermudagrass with >40% green cover appears susceptible to injury from flumioxazin at labeled use rates, but treatments could be safely applied when bermudagrass has <5% green cover regardless of application timing.

Centipedegrass. In 2012, centipedegrass had 4% (±1), 69% (±1), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively (Table 3.2). In 2013, centipedegrass had 1% (±0), 1% (±0), 99% (±1) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2012, all applications caused unacceptable injury to centipedegrass with injury ≥23% from all applications on at least one evaluation date (Table 3.3). Centipedegrass treated at PRE crabgrass timing had ≥60% injury at 3 WAT from all rates of flumioxazin. In 2013, late winter treatments during dormancy caused ≤10% injury. However, PRE crabgrass and mid-spring applications caused ≥25% injury at 6 WAT. Centipedegrass had substantial injury from applications of flumioxazin in mid-spring that linearly increased with rate. In 2012, centipedegrass was injured 60%, 99%, and 99%, at 0.21, 0.42, and 0.84 kg ai ha^{-1}, respectively at 3 WAT. In 2013, centipedegrass was injured 89%, 97%, and 99%, at 0.21, 0.42, and 0.84 kg ha^{-1}, respectively at 3 WAT.

Centipedegrass injury from flumioxazin lasted for an extended period, especially with mid-spring applications. Centipedegrass was injured 74% and 71% from applications at 0.84 kg ha^{-1} in mid-spring at 9 WAT in 2012 and 2013, respectively. Centipedegrass green cover reductions linearly increased with rate from PRE crabgrass timing in 2012, and mid-spring timing in both years. In 2012, green cover from grid counts was reduced 67% from the nontreated by flumioxazin at 0.84 kg ha^{-1} when applied in mid-spring. In 2013, applications made during late winter, PRE crabgrass, and mid-spring timings resulted in green cover reductions, although only mid-spring treatments reduced green cover ≥15%.

Flumioxazin may cause substantial damage during active growth and centipedegrass has shown similar sensitivity to oxadiazon. Turner et al. (1990) noted oxadiazon treatments at 2.2 and 4.5 kg ha^{-1} injured centipedegrass 21% and 71%, respectively, at 3 WAT. Flumioxazin treatments may be injurious to centipedegrass regardless of application timing, and do not appear to be a viable option for weed control.

Seashore paspalum. In 2012, seashore paspalum had 8% (±1), 63% (±3), 98% (±0) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively (Table 3.3). In 2013, seashore paspalum had 0% (±0), 5% (±1), 99% (±1) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. Late winter treatments to seashore paspalum caused ≤19% injury in both years. PRE crabgrass applications in 2012 and mid-spring treatments in both years caused ≥35% injury that linearly increased with rate at 1 WAT. At 3 WAT, injury to seashore paspalum from PRE crabgrass applications ranged 24 to 56% in 2012, but no injury was observed in 2013. At 3 WAT, mid-spring flumioxazin applications at 0.42 kg ai ha^{-1} caused 24% and 34% injury in 2012 and 2013, respectively. Treatments in mid-spring at 0.84 kg ai ha^{-1} caused 53% and 46% injury in 2012 and 2013, respectively, at 3 WAT. However, by 6 WAT, seashore paspalum was injured ≤19% from all applications and no treatment reduced seashore paspalum green cover in late June.

Seashore paspalum has shown tolerance to other Protox inhibitors, but tolerance to flumioxazin has not been reported. Johnson and Duncan (1998) noted oxadiazon applications at ≤10.1 kg ha^{-1} for summer annual weed control caused acceptable injury to seashore paspalum. McCullough et al. (2012b) found applications of sulfentrazone at 0.42 kg ai ha^{-1} caused <20% injury to actively growing 'Sea Isle I' seashore paspalum at 1 and 3 WAT. In other experiments, carfentrazone treatments caused <15% injury to seashore paspalum seedlings (Patton et al. 2009). Applications of flumioxazin may cause unacceptable injury to actively growing seashore paspalum, but treatments may be safely applied at <10% green cover.

St. Augustinegrass. In 2012, St. Augustinegrass had 23% (±1), 70% (±3), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively (Table 3.4). In 2013, St. Augustinegrass had 10% (±0), 4% (±2), 95% (±3) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. Late winter applications caused ≤16% injury in both years. At 1 WAT, PRE crabgrass treatments injured St. Augustinegrass 18 to 20% in 2012, but ≤3% in 2013. At 3 WAT, St. Augustinegrass injury from PRE crabgrass application timing ranged 15 to 24% in 2012, but there was no injury in 2013. In 2012, PRE crabgrass applications of 0.84 kg ai ha^{-1} caused 20% injury at 6 WAT, but applications caused only 5% injury in 2013. At 1 WAT, mid-spring applications caused >25% injury in both years. At 3 WAT, injury from mid-spring flumioxazin applications ranged 19 to 50% and 35 to 65% in 2012 and 2013, respectively. At 6 WAT, St. Augustinegrass recovered with ≤19% injury from all rates at the mid-spring timing, and was injured ≤5% at 9 WAT from all treatments. No flumioxazin application reduced St. Augustinegrass green cover in late June.

Turf managers may use several Protox inhibitors safely in St. Augustinegrass. Taylor et al. (2004) reported carfentrazone treatments caused acceptable injury to actively growing St. Augustinegrass on all dates evaluated. McCarty et al. (1995) noted St. Augustinegrass sod root biomass was not inhibited when planted in soil treated with oxadiazon at 1.7 and 3.4 kg ha^{-1}. St. Augustinegrass appears sensitive to flumioxazin during active growth, but applications at <25% green cover may have potential safety.

Zoysiagrass. In 2012, zoysiagrass had 4% (±1), 58% (±6), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively (Table 3.5). In 2013, zoysiagrass had 1% (±0), 1% (±0), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. Late winter applications to zoysiagrass caused ≤10% injury in both years. In 2012, PRE crabgrass and mid-spring applications caused >20% injury at 1 WAT. In 2012, PRE crabgrass treatments injured zoysiagrass 26 to 31% at 3 WAT, but never exceeded 6% in 2013. In 2013, only mid-spring treatments caused unacceptable injury at 1 WAT. Injury from mid-spring treatments linearly increased with rate and ranged 10 to 55% and 53 to 83% in 2012 and 2013, respectively, at 3 WAT. Applications of flumioxazin at PRE crabgrass and mid-spring timings at 0.21 and 0.42 kg ai ha^{-1} caused acceptable injury at 6 WAT in both years. In 2012, PRE crabgrass applications at 0.84 kg ha^{-1} caused 30% injury at 6 WAT, but was <7% in 2013. Mid-spring applications at 0.84 kg ha^{-1} injured zoysiagrass 55% and 83% at 3 WAT in 2012 and 2013, respectively, and turfgrass was injured ≥20% at 6 WAT in both years. However, zoysiagrass recovered and no treatment reduced green cover in late June.

Zoysiagrass may be safely treated with most Protox inhibitors during active growth (Fry et al. 1986). Oxadiazon may safely enhance turf quality by controlling weeds during zoysiagrass establishment, compared to the nontreated (Fry et al. 1986; Johnson and Carrow 1999). Patton et al. (2007) noted oxadiazon at 3.4 kg ha^{-1} injured seedling zoysiagrass, but turf recovered in less than 2 weeks. Actively growing zoysiagrass exhibited longer lasting injury from flumioxazin applications at >50% greenup. Flumioxazin applications to zoysiagrass with <5% green cover appear safe causing ≤10% injury, but actively growing turfgrass may be excessively injured.

Conclusion

Late winter flumioxazin applications caused minimal injury to bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass on all evaluation dates in both years. Centipedegrass injury from late winter timings was inconsistent over years, but results suggest injury may be substantial at later spring timings. Environmental conditions were variable between years with cooler temperatures in 2013 than in 2012. This temperature effect in 2013 resulted in delayed greenup, and probably reduced injury potential from late winter and PRE crabgrass timings. PRE crabgrass applications in 2012 and mid-spring applications in both years initially caused unacceptable injury to all warm-season turfgrasses. However, bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass recovered by 9 WAT from all rates.

Mid-spring applications to centipedegrass resulted in thinning and stand loss, especially at 0.84 kg ai ha^{-1}.

Flumioxazin may be applicable for controlling annual bluegrass in bermudagrass and other warm-season turfgrasses with late winter applications with minimal (<20%) green cover. Flumioxazin may have an extended period of safety on warm-season turfgrasses during years of delayed greenup due to low temperatures, but all turfgrasses may be injured during active growth. Bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass may recover from injury by flumioxazin after greenup, but centipedegrass appears potentially sensitive at all timings.

Results advocate expanding the current turfgrass label for flumioxazin use in dormant seashore paspalum and zoysiagrass. St. Augustinegrass may also be tolerant, but there is risk of injury if turf has >20% green cover at application. Further research is warranted to determine if granular formulations could minimize turfgrass injury compared to sprayable treatments. Currently, oxadiazon is labeled in sprayable formulations to dormant warm-season turf, but only granular formulations may be used after greenup. Perhaps granular formulations of flumioxazin could be safely applied after turf greenup for weed control, and warrants further investigation.

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Table 3.1. ‘Tifway’ bermudagrass injury and green cover reductions from flumioxazin applications at three timings in field experiments, 2012-2013, Griffin, GA.

			Injury (WAT[a])									
			2012				2013				Green Cover Reduction[d]	
Application Timing[b]	Rate		1[c]	3	6	9	1	3	6	9	2012	2013
	kg ai ha^{-1}		%									
Late Winter	0.21			0	0	2		0	0	0	0	0
	0.42			0	0	1		0	0	0	0	0
	0.84			0	6	5		0	0	0	0	0
PRE Crabgrass	0.21		38	11	0	0	3	0	0	0	0	0
	0.42		46	23	5	0	5	0	0	0	0	0
	0.84		54	34	9	0	8	0	0	0	0	0
Mid-Spring	0.21		66	3	1	0	89	13	4	0	0	0
	0.42		73	6	3	0	90	16	5	1	0	0
	0.84		78	11	5	0	93	21	10	1	0	0
$LSD_{0.05}$			9	6	4	3	6	8	6	1	NS	NS
	Timing		*	*	NS	*	*	*	*	NS	NS	NS
	Rate		*	*	*	NS	NS	NS	NS	NS	NS	NS
		Linear	*		*	NS	NS	NS	NS	NS	NS	NS
		Quadratic	NS		NS	NS	NS	NS	NS	NS	NS	NS
	Timing*Rate		NS	*	NS	NS	NS	NS	NS	NS	NS	NS
Late Winter	Rate	Linear		NS								
		Quadratic		NS								
PRE Crabgrass	Rate	Linear		*								
		Quadratic		NS								
Mid-Spring	Rate	Linear		*								
		Quadratic		NS								

[a]WAT = weeks after treatment.

[b]In 2012, applications were made February 2, March 16, or April 27 for late winter, PRE crabgrass, late spring, respectively. In 2013, applications were made February 1, March 14, or April 26. In 2012, bermudagrass had 4% (±1), 46% (±3), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2013, bermudagrass had 0% (±0), 2% (±1), 100% (±0) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively.

[c]Due to dormancy of turfgrass, injury was not evaluated for late winter timing at 1 WAT.

[d]Green cover in grid counts were taken June 29 and June 28 for 2012 and 2013, respectively, and presented as a percent reduction from nontreated.

Means were separated with Fisher’s Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate.

PRE = Preemergence; LSD = least significant difference; * = significant; NS = not significant.

Table 3.2. ‘TifBlair’ centipedegrass injury and green cover reductions from flumioxazin applications at three timings in field experiments, 2012-2013, Griffin, GA.

			Injury (WAT[a])									
			2012				2013				Green Cover Reduction[d]	
Application Timing[b]	Rate		1[c]	3	6	9	1	3	6	9	2012	2013
	kg ai ha^{-1}		———	———	———	———	%	———	———	———	———	———
Late Winter	0.21			6	23	0		0	0	0	0	4
	0.42			8	30	1		0	0	0	0	0
	0.84			8	45	4		0	0	0	0	4
PRE Crabgrass	0.21		66	64	24	0	0	0	25	21	0	5
	0.42		69	69	56	5	0	0	26	20	0	6
	0.84		73	75	94	59	0	0	29	19	27	0
Mid-Spring	0.21		69	60	5	0	98	89	34	13	0	15
	0.42		83	99	56	24	97	97	68	48	19	30
	0.84		88	99	94	74	99	99	94	71	67	56
$LSD_{0.05}$			12	10	19	22	2	3	17	23	17	16
	Timing		*	*	*	*	*	*	*	*	*	*
	Rate		*	*	*	*	NS	*	*	*	*	*
		Linear	*				NS					
		Quadratic	NS				NS					
	Timing*Rate		NS	*	*	*	NS	*	*	*	*	*
Late Winter	Rate	Linear		NS	*	*		NS	NS	NS	NS	NS
		Quadratic		NS	NS	NS		NS	NS	NS	NS	NS
PRE Crabgrass	Rate	Linear		NS	*	*		NS	NS	NS	*	NS
		Quadratic		NS	NS	*		NS	NS	NS	NS	NS
Mid-Spring	Rate	Linear		*	*	*		*	*	*	*	*
		Quadratic		*	NS	NS		NS	NS	NS	NS	NS

[a]WAT = weeks after treatment.

[b]In 2012, applications were made February 2, March 16, or April 27 for late winter, PRE crabgrass, late spring, respectively. In 2013, applications were made February 1, March 14, or April 26. In 2012, centipedegrass had 4% (±1), 69% (±1), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2013, centipedegrass had 1% (±0), 1% (±0), 99% (±1) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively.

[c]Due to dormancy of turfgrass, injury was not evaluated for late winter timing at 1 WAT.

[d]Green cover in grid counts were taken June 29 and June 28 for 2012 and 2013, respectively, and presented as a percent reduction from nontreated.

Means were separated with Fisher’s Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate.

PRE = Preemergence; LSD = least significant difference; * = significant; NS = not significant.

Table 3.3. ‘Sea Isle I’ seashore paspalum injury and green cover reductions from flumioxazin applications at three timings in field experiments, 2012-2013, Griffin, GA.

			Injury (WAT[a])									
			2012				2013				Green Cover Reduction[d]	
Application Timing[b]	Rate		1[c]	3	6	9	1	3	6	9	2012	2013
	kg ai ha^{-1}		%									
Late Winter	0.21			0	0	9		0	0	0	0	0
	0.42			0	0	14		0	0	0	0	0
	0.84			0	10	19		0	0	0	0	0
PRE Crabgrass	0.21		54	24	4	0	0	0	3	0	0	0
	0.42		64	45	10	0	0	0	3	1	0	0
	0.84		69	56	18	0	0	0	19	5	0	0
Mid-Spring	0.21		35	8	0	0	65	14	1	0	0	0
	0.42		43	24	0	0	76	34	3	0	0	0
	0.84		48	53	10	0	79	46	10	1	0	0
$LSD_{0.05}$			14	15	8	6	7	9	7	2	NS	NS
	Timing		*	*	*	*	*	*	*	*	NS	NS
	Rate		*	*	*	NS	*	*	*	*	NS	NS
		Linear	*		*	NS	*			*	NS	NS
		Quadratic	NS		NS	NS	NS			NS	NS	NS
	Timing*Rate		NS	*	NS	NS	NS	*	*	NS	NS	NS
Late Winter	Rate	Linear		NS				NS	NS			
		Quadratic		NS				NS	NS			
PRE Crabgrass	Rate	Linear		*				NS	*			
		Quadratic		NS				NS	NS			
Mid-Spring	Rate	Linear		*				*	*			
		Quadratic		NS				NS	NS			

[a]WAT = weeks after treatment.

[b]In 2012, applications were made February 2, March 16, or April 27 for late winter, PRE crabgrass, late spring, respectively. In 2013, applications were made February 1, March 14, or April 26. In 2012, seashore paspalum had 8% (±1), 63% (±3), 98% (±0) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2013, seashore paspalum had 0% (±0), 5% (±1), 99% (±1) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively.

[c]Due to dormancy of turfgrass, injury was not evaluated for late winter timing at 1 WAT.

[d]Green cover in grid counts were taken June 29 and June 28 for 2012 and 2013, respectively, and presented as a percent reduction from nontreated.

Means were separated with Fisher’s Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate.

PRE = Preemergence; LSD = least significant difference; * = significant; NS = not significant.

Table 3.4. ‘Palmetto’ St. Augustinegrass injury and green cover reductions from flumioxazin applications at three timings in field experiments, 2012-2013, Griffin, GA.

			Injury (WAT[a])									
			2012				2013				Green Cover Reduction[d]	
Application Timing[b]	Rate		1[c]	3	6	9	1	3	6	9	2012	2013
	kg ai ha^{-1}		%									
Late Winter	0.21			15	0	3		0	0	0	0	0
	0.42			15	0	3		0	0	0	0	0
	0.84			16	0	1		0	0	0	0	0
PRE Crabgrass	0.21		18	15	9	0	3	0	1	1	0	0
	0.42		18	19	14	0	3	0	3	3	0	0
	0.84		20	24	20	1	3	0	5	5	0	0
Mid-Spring	0.21		30	19	5	0	26	35	6	0	0	0
	0.42		33	28	8	0	35	60	10	2	0	0
	0.84		43	50	19	4	36	65	19	4	0	0
$LSD_{0.05}$			10	8	6	3	10	9	5	3	NS	NS
	Timing		*	*	*	NS	*	*	*	*	NS	NS
	Rate		*	*	*	NS	NS	*	*	*	NS	NS
		Linear	*			NS	NS			*	NS	NS
		Quadratic	NS			NS	NS			NS	NS	NS
	Timing*Rate		NS	*	*	NS	NS	*	*	NS	NS	NS
Late Winter	Rate	Linear		NS	NS			NS	NS			
		Quadratic		NS	NS			NS	NS			
PRE Crabgrass	Rate	Linear		NS	*			NS	NS			
		Quadratic		NS	NS			NS	NS			
Mid-Spring	Rate	Linear		*	*			*	*			
		Quadratic		*	NS			NS	NS			

[a]WAT = weeks after treatment.

[b]In 2012, applications were made February 2, March 16, or April 27 for late winter, PRE crabgrass, late spring, respectively. In 2013, applications were made February 1, March 14, or April 26. In 2012, St. Augustinegrass had 23% (±1), 70% (±3), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2013, St. Augustinegrass had 10% (±0), 4% (±2), 95% (±3) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively.

[c]Due to dormancy of turfgrass, injury was not evaluated for late winter timing at 1 WAT.

[d]Green cover in grid counts were taken June 29 and June 28 for 2012 and 2013, respectively, and presented as a percent reduction from nontreated.

Means were separated with Fisher’s Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate.

PRE = Preemergence; LSD = least significant difference; * = significant; NS = not significant.

Table 3.5. ‘Zeon’ zoysiagrass injury and green cover reductions from flumioxazin applications at three timings in field experiments, 2012-2013, Griffin, GA.

			Injury (WAT[a])									
			2012				2013				Green Cover Reduction[d]	
Application Timing[b]	Rate		1[c]	3	6	9	1	3	6	9	2012	2013
	kg ai ha^{-1}		%									
Late Winter	0.21			10	3	3		0	0	0	0	0
	0.42			10	3	1		0	0	0	0	0
	0.84			10	8	8		0	0	0	0	0
PRE Crabgrass	0.21		21	26	8	0	0	0	4	1	0	0
	0.42		23	29	18	0	0	0	3	0	0	0
	0.84		23	31	30	0	0	0	6	0	0	0
Mid-Spring	0.21		22	10	19	0	69	53	5	0	0	0
	0.42		25	31	15	3	75	74	10	1	0	0
	0.84		30	55	33	5	71	83	26	3	0	0
$LSD_{0.05}$			8	11	15	3	6	7	6	2	NS	NS
	Timing		NS	*	*	*	*	*	*	NS	NS	NS
	Rate		NS	*	*	*	NS	*	*	NS	NS	NS
		Linear	NS		*		NS				NS	NS
		Quadratic	NS		NS		NS				NS	NS
	Timing*Rate		NS	*	NS	*	NS	*	*	*	NS	NS
Late Winter	Rate	Linear		NS		*		NS	NS	NS		
		Quadratic		NS		*		NS	NS	NS		
PRE Crabgrass	Rate	Linear		NS		NS		NS	NS	NS		
		Quadratic		NS		NS		NS	NS	NS		
Mid-Spring	Rate	Linear		*		*		*	*	*		
		Quadratic		NS		NS		NS	NS	NS		

[a]WAT = weeks after treatment.

[b]In 2012, applications were made February 2, March 16, or April 27 for late winter, PRE crabgrass, late spring, respectively. In 2013, applications were made February 1, March 14, or April 26. In 2012, zoysiagrass had 4% (±1), 58% (±6), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively. In 2013, zoysiagrass had 1% (±0), 1% (±0), 96% (±2) green cover at late winter, PRE crabgrass, and mid-spring timings, respectively.

[c]Due to dormancy of turfgrass, injury was not evaluated for late winter timing at 1 WAT.

[d]Green cover in grid counts were taken June 29 and June 28 for 2012 and 2013, respectively, and presented as a percent reduction from nontreated.

Means were separated with Fisher’s Protected LSD Test at $\alpha = 0.05$. Orthogonal polynomial contrasts were used to evaluate relationship of turfgrass response with flumioxazin rate.

PRE = Preemergence; LSD = least significant difference; * = significant; NS = not significant.

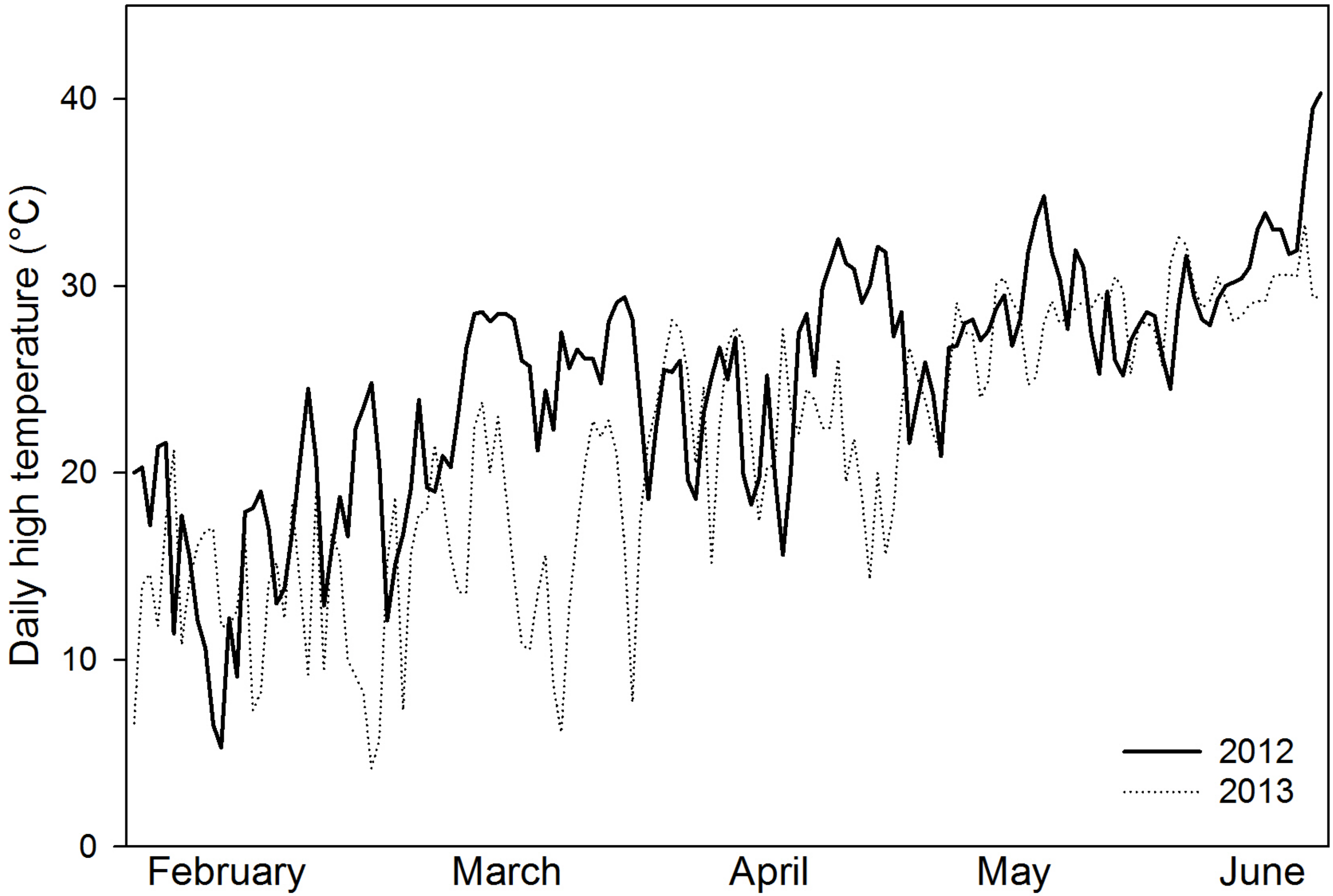

Figure 3.1. Daily high air temperatures for Griffin, GA, during the experimental period of February through June in 2012 and 2013.

CHAPTER 4

EVALUATION OF ADJUVANTS ON FLUMIOXAZIN EFFICACY FOR POSTEMERGENCE ANNUAL BLUEGRASS AND RESIDUAL SMOOTH CRABGRASS CONTROL[3]

[3] T. V. Reed, P. McCullough, and T. Grey. Submitted to *Applied Turfgrass Science*, 10/25/13.

Abstract

Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor with potential for postemergence (POST) annual bluegrass (*Poa annua* L.) control and preemergence (PRE) smooth crabgrass (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) control in bermudagrass (*Cynodon dactylon* (L.) Pers.). However, flumioxazin efficacy is reduced under low temperatures and applications are often inconsistent on mature annual bluegrass. The objective of this research was to evaluate the use of adjuvants on flumioxazin efficacy for POST annual bluegrass and residual smooth crabgrass control. Tank-mixing methylated seed oil, nonionic surfactant, or ammonium sulfate did not improve POST annual bluegrass control from flumioxazin at 0.42 kg ai ha^{-1} alone. Granular urea antagonized flumioxazin efficacy and increased the time to achieve 50% annual bluegrass control (C_{50}) by >4 weeks. Flumioxazin-only treatments controlled annual bluegrass >80% in both years at 9 weeks after treatment (WAT). All flumioxazin applications provided excellent (90 to 100%) control of smooth crabgrass at 4 months after treatment (MAT) and ≥89% control at 5 MAT. All flumioxazin treatments provided >70% smooth crabgrass control, and reduced grid count cover >65% from the nontreated at 7 MAT. Overall, annual bluegrass control from late winter flumioxazin applications were not improved by adjuvants, but flumioxazin may provide >80% POST annual bluegrass and PRE smooth crabgrass control.

Introduction

Annual bluegrass (*Poa annua* L.) is a problematic weed in intensively managed turf (Lush 1989). Annual bluegrass compromises the aesthetics and utility of turfgrasses with its bunch-type growth habit, light green color, and poor stress tolerance (Beard et al. 1978; Lush

1989; Sweeney and Danneberger 1997). As annual bluegrass declines in spring, summer annuals such as smooth crabgrass (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) can establish and further reduce turf quality (Johnson 1996; McCarty et al. 2008; Tae-Joon et al. 2002). Controlling established annual bluegrass often requires use of postemergence (POST) herbicides. However, annual bluegrass has developed resistance to several herbicide chemistries including glyphosate, sulfonylureas, and triazines (Brosnan et al. 2012; Cross et al. 2013; Darmency and Gasquez 1981; Heap 1997). Thus, different mechanisms of action would be beneficial for POST annual bluegrass control in turf.

Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor that offers an alternative mechanism of action to other herbicide chemistries for POST annual bluegrass control in bermudagrass (*Cynodon dactylon* (L.) Pers.) (Flessner et al. 2013). Inhibition of the Protox enzyme in chlorophyll biosynthesis leads to loss of membrane integrity, resulting in cell death of susceptible species (Duke et al. 1991; Scalla and Matringe 1994). Other Protox inhibitors registered for turfgrass include carfentrazone, oxadiazon, and sulfentrazone, but none of these herbicides provide POST annual bluegrass control at registered rates (Isgrigg et al. 2002; Senseman 2007; Toler et al. 2003). Moreover, flumioxazin has shown preemergence (PRE) control of smooth crabgrass; and thus has potential as an effective tool in turf weed control programs (McCullough et al. 2012).

Flumioxazin may provide significant control of annual bluegrass with early winter treatments in the Southern United States, but efficacy is often reduced with late winter or early spring applications (Flessner et al. 2013; McCullough et al. 2012). Since flumioxazin is applied during winter months, as noted with other POST herbicides. Previous research has shown annual bluegrass susceptibility to POST herbicides may be influenced by temperature. For example, amicarbazone and bispyribac-sodium applications caused greater annual bluegrass injury as temperature increased from 10 to 30° C (McCullough and Hart 2006; McCullough et al. 2010). Efficacy of Protox inhibiting herbicides, such as flumiclorac and fluthiacet, also increases with temperature on susceptible weeds including redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) (Fausey and Renner 2001). Reduction in flumioxazin efficacy may also result from annual bluegrass maturity at winter applications. Flessner et al. (2013) reported annual bluegrass with two tillers or less was controlled ≥95% with flumioxazin applications at 0.43 kg ai ha^{-1}. However, annual bluegrass with four to six tillers was controlled <50% from flumioxazin applications at 0.43 kg ai ha^{-1}.

Spray adjuvants are tank-mixed with herbicides to increase foliar absorption by reducing surface tension of spray droplets that enhances herbicide retention and spread over leaf surfaces (Ferrell and Vencill 2003; Wanamarta and Penner 1989). Adjuvants have potential to improve POST control of grassy weeds with herbicides. McCullough and Hart (2008) noted adjuvants increased foliar absorption and efficacy on annual bluegrass with bispyribac-sodium. Wehtje and Walker (2002) reported nonionic surfactant use with rimsulfuron at 0.018 kg ai ha^{-1} improved annual bluegrass control >10%, compared to treatments without adjuvants. Practices that promote growth, such as nitrogen fertilization may enhance herbicide efficacy (Dickson et al. 1990; Gallaher et al. 1999). Brosnan et al. (2010) noted that urea at 73 kg ha^{-1} increased control and translocation of flazasulfuron in annual bluegrass. Thus, adjuvants may help overcome the limitations of low temperature and growth stage on flumioxazin efficacy for annual bluegrass control. However, comprehensive investigations are required to enhance flumioxazin efficacy on mature annual bluegrass from winter applications. The objective of this research was to evaluate the use of adjuvants on flumioxazin efficacy for POST annual bluegrass control from winter applications, and residual smooth crabgrass control.

Materials and Methods

Field experiments were conducted in Griffin, GA (33.26°N, 84.28°W), from February to September in 2012 and 2013. Soil was a Cecil sandy clay loam soil (fine, kaolinitic, thermic Typic Kanhapludults) with 2.5% organic matter and a pH of 6.0. Experiments were conducted on ‘Tifsport’ bermudagrass and were mowed during active growth with reel-mowers at 1.3 cm two days per week. Fields had clippings returned and were irrigated as needed to prevent turf wilting. Plots in 2013 were adjacent to plots in 2012.

Treatments included flumioxazin (SureGuard® 51WG, Valent U.S.A. Corporation, Walnut Creek, CA) at 0.42 kg ai ha^{-1} alone or in combination with one or more adjuvants and nitrogen sources: nonionic surfactant (NIS) (Chem Nut 80-20, 80% alkyl polyoxyethylene ether, Chem Nut Inc., Albany, GA) at 0.25% v/v, methylated seed oil (MSO) (MES-100, 100% methylated seed oil, alkylphenol ethoxylate, Drexel Chemical Company, Memphis, TN) at 1.0% v/v, ammonium sulfate (AMS) (S-Sul Sprayable Ammonium Sulfate 21-0-0, 99.5% ammonium sulfate, American Plant Food Corp., Galena Park, TX) at 9.0 kg ha^{-1}, and granular urea (Professional Turf Fertilizer 46-0-0, 46% urea nitrogen, Lesco, Cleveland, OH) at 73.2 kg ha^{-1}. Applications were made February 3 in 2012 and February 1 in 2013. Herbicide treatments were applied by a CO_2-pressured backpack sprayer calibrated to deliver 374 L ha^{-1} with a single 9504E flat-fan nozzle (Tee Jet, Spraying Systems Co., Roswell, GA). Granular urea was applied by hand before herbicide treatments.

Experimental design was a randomized complete block with four replications of 1 x 3-m plots. Annual bluegrass and crabgrass control was visually rated on a percent scale where 0 equaled no control and 100 equaled complete control from nontreated plots. Visual ratings were taken 1, 2, 3, 4, 6, 9, and 12 weeks after treatment (WAT) for annual bluegrass control. Data were subjected to analysis of variance in SAS (SAS® Institute v. 9.3, Cary, NC). Predicted time for treatments to provide 50% control (C_{50}) was determined with nonlinear regression analysis using SigmaPlot (Systat Software Inc. SigmaPlot v. 11.0, San Jose, CA), with polynomial, quadratic equation: $y = a + bx + cx^2$ where y is control from the nontreated expressed as a percentage, a, b, and c are constants, and x is time in weeks. Year by treatment interactions were detected for annual bluegrass control, and thus years are presented independently. Means of predicted C_{50} values were separated using Fisher's Protected LSD Test at $\alpha = 0.05$.

Evaluations for smooth crabgrass control were made 4, 5, 6, and 7 months after treatment (MAT). Smooth crabgrass cover was taken with grid counts on August 30 in 2012 and September 2 in 2013, and presented as a percent reduction from the nontreated by replication. Grids with crabgrass present were counted in two samples per plot with a 0.58-m^2 sampling grid containing 36-12.7 x 12.7-cm grids. Data were subjected to analysis of variance at the 0.05 probability level in SAS. Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$. Year by treatment interactions were not detected for smooth crabgrass control and, thus years are combined.

Results and Discussion

Annual Bluegrass Control. Bermudagrass injury was not detected on any evaluation date (data not shown). On the day of application, annual bluegrass cover across all plots was 44% (±1) and 24% (±1) in 2012 and 2013, respectively. Flumioxazin-only applications required 2.6 and 1.7

weeks to obtain 50% annual bluegrass control in 2012 and 2013, respectively (Table 4.1). No adjuvant or nitrogen combination significantly reduced the time to achieve 50% annual bluegrass control. However, annual bluegrass control was antagonized by urea. Flumioxazin treatments with urea alone had C_{50} values of 6.8 and 8.0 weeks in 2012 and 2013, respectively. In 2013, flumioxazin with NIS plus urea provided <50% control.

Flumioxazin-only treatments controlled annual bluegrass >80% in both years at 12 WAT. In 2012, all treatments provided >85% annual bluegrass control at 12 WAT (Figure 4.1). In 2013, flumioxazin with urea or NIS plus urea were the only treatments that provided <80% control. Similar results were noted by Flessner et al. (2013) in Alabama and California. The researchers reported early February applications of flumioxazin at 0.43 kg ha^{-1} with a nonionic surfactant at 0.25% v/v provided 60% and 72% annual bluegrass control at 1 and 2 MAT, respectively.

Controlling actively growing annual bluegrass in dormant bermudagrass may be advantageous in preventing weed establishment and maintaining turf density (Bingham et al. 1969; Johnson 1980). Flumioxazin treatments with adjuvants or nitrogen sources did not improve speed of annual bluegrass control from flumioxazin treatments alone. This is similar to previous research with flumioxazin treatments with adjuvants. In cotton (*Gossypium hirsutum* L.), Ferrell and Vencill (2003) noted POST flumioxazin applications with ammonium sulfate, methylated seed oil, and nonionic surfactant did not increase control of sicklepod (*Senna obtusifolia* L.), tall morningglory (*Ipomoea purpurea* (L.) Roth), Texas panicum (*Panicum texanum* Buckl.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), and yellow nutsedge (*Cyperus esculentus* L.) compared to flumioxazin alone at 45 DAT.

In previous investigation, root uptake was critical for maximizing flumioxazin efficacy for annual bluegrass control (Chapter 2). Soil-only and soil-plus-foliar applications of flumioxazin at 0.42 kg ha^{-1} provided 25% greater control of annual bluegrass than foliar-only treatments. Adjuvants may have minimal potential to increase flumioxazin efficacy due to affinity for root uptake in annual bluegrass. An alternative option may be to tank-mix flumioxazin with other POST annual bluegrass herbicides with different mechanisms of action. This could enhance control on mature annual bluegrass with late winter applications of flumioxazin and provide residual control of smooth crabgrass or other annual weeds.

Smooth Crabgrass Control. Smooth crabgrass cover increased from May to September, and was 18% (±8) and 56% (±8) in 2012 and 2013, respectively, in nontreated plots at 7 MAT (Table 4.2). All flumioxazin applications provided excellent (90 to 100%) control of smooth crabgrass at 4 MAT and ≥89% control at 5 MAT in both years. All flumioxazin treatments provided >70% smooth crabgrass control and had >65% grid count reductions from the nontreated at 7 MAT. Although flumioxazin controlled annual bluegrass in winter, PRE smooth crabgrass control was high enough to provide five to six months control at acceptable levels. Perhaps, delayed flumioxazin treatments in late March or April could provide season-long smooth crabgrass control, and warrants further investigation.

Smooth crabgrass control was variable between years due to greater weed pressure and rainfall in 2013 than in 2012 (Table 4.3). In 2013, greater rainfall may have increased smooth crabgrass pressure and reduced flumioxazin residual activity (Alister et al. 2008; Ferrell et al. 2005). In both years, smooth crabgrass control was ≥88% at 5 MAT. However, at 6 MAT, control averaged 94% and 76% across treatments in 2012 and 2013, respectively. Smooth crabgrass control and grid count reductions were 98% and 88% at 7 MAT in 2012, respectively, but were only 66% and 57% in 2013, respectively.

Smooth crabgrass control from flumioxazin was similar to previous research. McCullough et al. (2012) and Warren et al. (2013) reported flumioxazin at 0.42 kg ai ha^{-1} had >80% smooth crabgrass control in September from March applications. McCurdy et al. (2008) reported another Protox inhibitor, oxadiazon at 4.48 kg ha^{-1}, provided 92% control of smooth crabgrass at the end of August from March applications. Similar results were noted by Johnson (1976) from oxadiazon at 4.50 kg ha^{-1} for PRE crabgrass control. Flumioxazin efficacy for PRE smooth crabgrass has received limited reporting in scientific literature, but late winter applications may provide five to six months of PRE smooth crabgrass control in turfgrass.

Dithiopyr, pendimethalin, and prodiamine are mitotic inhibiting herbicides that are frequently used for PRE smooth crabgrass control. These herbicides have potential to exacerbate root growth inhibition of turfgrass from winterkill or disease in spring (Fishel and Coats 1993; Landschoot et al. 2003; Senseman 2007). When applied to dormant bermudagrass, flumioxazin could effectively control smooth crabgrass with better safety on lateral rooting during spring greenup than dinitroaniline or pyridine herbicides, similar to oxadiazon. Further investigation is needed to evaluate turf safety, rooting, and recovery from winter injury following flumioxazin treatments.

Conclusion

Flumioxazin has potential for POST annual bluegrass control, but low temperatures and annual bluegrass maturity may influence winter applications. Applications in winter or spring could reduce herbicide use in turf by providing residual summer annual weed control.

Flumioxazin appears effective for PRE smooth crabgrass control, and may control other summer annual weeds when used for POST annual bluegrass control in winter. Overall, adjuvants did not enhance speed of annual bluegrass control, but flumioxazin-only treatments controlled annual bluegrass >80% and provided >80% PRE smooth crabgrass control.

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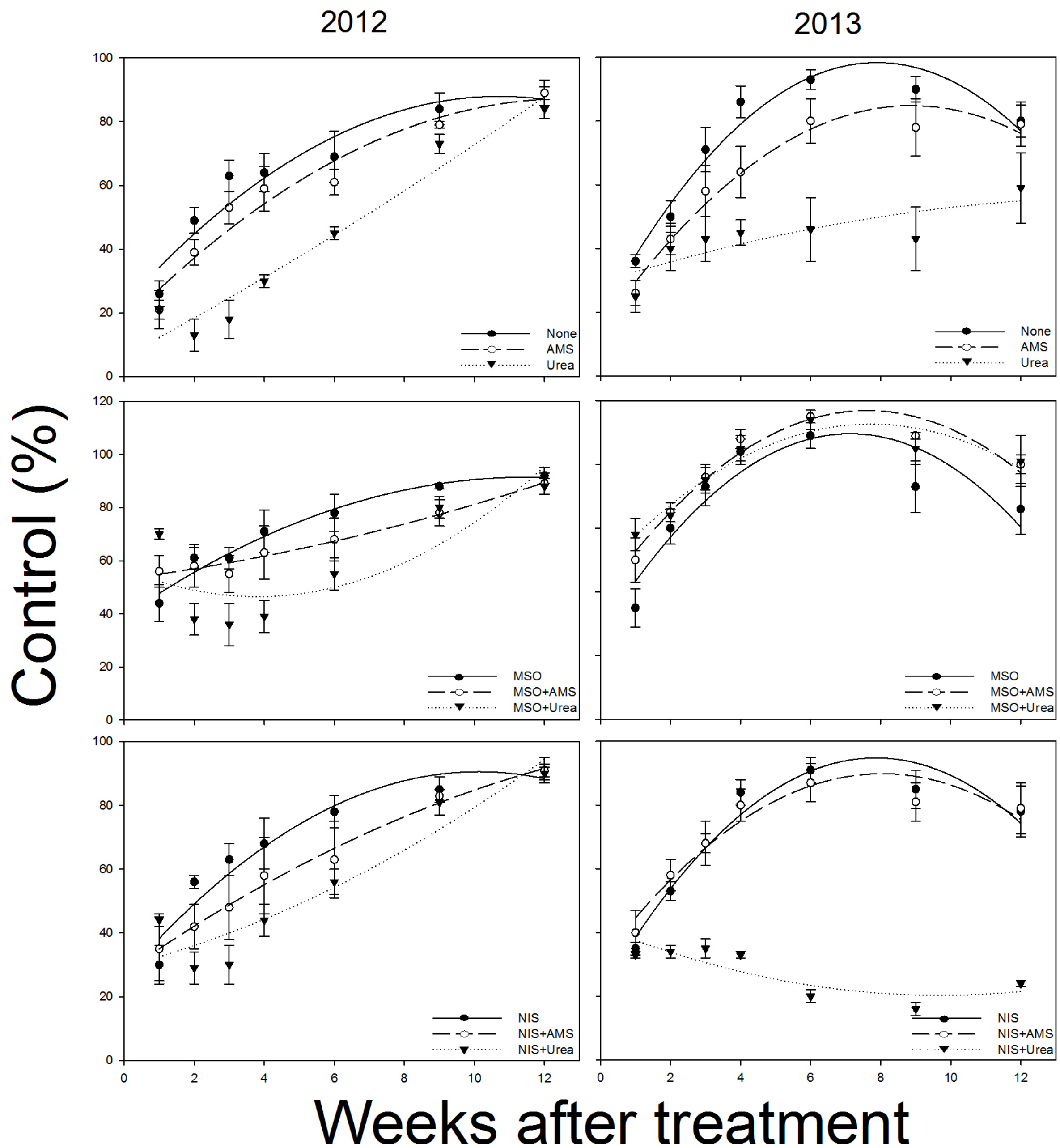

Figure 4.1. Annual bluegrass control following flumioxazin applications with adjuvants in field experiments, 2012-2013, Griffin, GA. Error bars represent standard error of the mean. Nonlinear regression equations are listed in Table 4.1. Abbreviations, MSO: methylated seed oil; NIS: nonionic surfactant; AMS: ammonium sulfate.

Table 4.1. Predicted time required for flumioxazin with adjuvants for 50% annual bluegrass control (C_{50}) in field experiments, 2012-2013, Griffin, GA.

Adjuvant[a]	Nitrogen[b]	C_{50} 2012	C_{50} 2013
		weeks	weeks
-	-	2.6	1.7
-	AMS	3.5	2.7
-	Urea	6.8	8.0
MSO	-	1.3	1.5
	AMS	<1.0	<1.0
	Urea	<1.0	<1.0
NIS	-	2.1	1.8
	AMS	3.2	1.5
	Urea	5.2	>12.0
	$LSD_{0.05}$	2.9	2.7
		Equations[d]	
-	-	$y = 22.81 + 12.04x - 0.56x^2$ $r^2 = 0.76$; SE[c] = 11.06	$y = 19.07 + 20.14x - 1.28x^2$ $r^2 = 0.83$; SE = 9.50
-	AMS	$y = 16.67 + 11.11x - 0.44x^2$ $r^2 = 0.84$; SE = 9.69	$y = 14.53 + 15.74x - 0.89x^2$ $r^2 = 0.65$; SE = 14.33
-	Urea	$y = 6.25 + 5.85x + 0.08x^2$ $r^2 = 0.89$; SE = 9.27	$y = 29.21 + 3.47x - 0.11x^2$ $r^2 = 0.08$; SE = 26.82
MSO	-	$y = 39.33 + 8.96x - 0.39x^2$ $r^2 = 0.72$; SE = 10.15	$y = 27.17 + 17.32x - 1.21x^2$ $r^2 = 0.51$; SE = 15.45
	AMS	$y = 53.34 + 1.52x + 0.12x^2$ $r^2 = 0.44$; SE = 13.78	$y = 38.46 + 15.25x - 1.00x^2$ $r^2 = 0.79$; SE = 7.54
	Urea	$y = 56.81 - 5.47x + 0.72x^2$ $r^2 = 0.56$; SE = 15.41	$y = 46.07 + 11.95x - 0.77x^2$ $r^2 = 0.61$; SE = 9.57
NIS	-	$y = 26.43 + 12.48x - 0.61x^2$ $r^2 = 0.77$; SE = 10.48	$y = 20.52 + 18.88x - 1.20x^2$ $r^2 = 0.78$; SE = 10.30
	AMS	$y = 27.29 + 7.82x - 0.20x^2$ $r^2 = 0.65$; SE = 15.21	$y = 30.20 + 14.88x - 0.93x^2$ $r^2 = 0.62$; SE = 12.28
	Urea	$y = 28.97 + 3.02x + 0.20x^2$ $r^2 = 0.80$; SE = 10.97	$y = 41.11 - 4.24x + 0.22x^2$ $r^2 = 0.42$; SE = 7.25

[a]Adjuvant concentrations, MSO at 1.0% v/v; NIS at 0.25% v/v.

[b]Nitrogen rates, AMS at 9.0 kg ha^{-1}; Urea (granular) at 73.2 kg ha^{-1}.

[c]SE = standard errors of the estimate.

[d]Nonlinear regression analysis using polynomial, quadratic equation: $y = a + bx + cx^2$ where *y* is control from the nontreated expressed as a percentage, *a*, *b*, and *c* are constants, and *x* is time in weeks.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$.

Flumioxazin applications at 0.42 kg ai ha^{-1} were made February 3 in 2012 and February 1 in 2013.

Abbreviations, MSO = methylated seed oil; NIS = nonionic surfactant; AMS = ammonium sulfate; LSD = least significant difference.

Table 4.2. Smooth crabgrass control and grid count reductions from nontreated following flumioxazin applications with adjuvants in two combined field experiments, 2012-2013, Griffin, GA.

		Control (MAT[a])				Grid Count[b]
Adjuvant[c]	Nitrogen[d]	4	5	6	7	7
		%				
-	-	96	91	86	83	66
-	AMS	91	89	73	71	66
-	Urea	97	95	89	80	72
MSO	-	98	95	91	84	78
	AMS	98	97	89	86	76
	Urea	99	97	91	88	80
NIS	-	94	92	83	83	70
	AMS	98	96	87	83	74
	Urea	94	92	80	79	71
	$LSD_{0.05}$	6	7	14	17	19
Year						
2012		100	100	94	98	88
2013		92	88	76	66	57
	$LSD_{0.05}$	3	3	7	8	9

[a]MAT = months after treatment.

[b]Two samples were taken in each plot with a 0.58-m^2 grid comprising 36-12.7 x 12.7-cm grids.

[c]Adjuvant concentrations, MSO at 1.0% v/v; NIS at 0.25% v/v.

[d]Nitrogen rates, AMS at 9.0 kg ha^{-1}; Urea (granular) at 73.2 kg ha^{-1}.

Flumioxazin applications at 0.42 kg ai ha^{-1} were made February 3 in 2012 and February 1 in 2013. Smooth crabgrass cover was 18% (±8) and 56% (±8) in 2012 and 2013, respectively, in nontreated plots at 7 MAT.

Means were separated with Fisher's Protected LSD Test at α = 0.05.

Abbreviations, MSO = methylated seed oil; NIS = nonionic surfactant; AMS = ammonium sulfate; LSD = least significant difference.

Table 4.3. Rainfall by month during experimental period in two field experiments, 2012-2013, Griffin, GA.

	Rainfall (cm)							
Year	February	March	April	May	June	July	August	Total
2012	9.4	9.0	1.0	8.1	4.7	13.2	17.7	63.1
2013	22.2	9.9	11.9	14.5	18.6	21.0	9.3	107.4

Applications were made February 3 in 2012 and February 1 in 2013.

Final evaluation dates for crabgrass control were September 5 in 2012 and September 2 in 2013.

CHAPTER 5

EVALUATION OF FLUMIOXAZIN TANK-MIXTURES WITH SIX HERBICIDES FOR ANNUAL BLUEGRASS AND SMOOTH CRABGRASS CONTROL[4]

[4] T. V. Reed, P. McCullough, T. Grey, M. Czarnota, W. Vencill, and C. Waltz. To be submitted to *Weed Technology*.

Abstract

Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor with potential for postemergence (POST) annual bluegrass (*Poa annua* L.) control and preemergence (PRE) smooth crabgrass (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) control in bermudagrass (*Cynodon dactylon* (L.) Pers.). However, efficacy is often reduced on tillered annual bluegrass in winter. Tank-mixtures could improve control from flumioxazin alone or help control biotypes with resistance to other chemistries. The objective of this research was to evaluate tank-mixtures of flumioxazin with six other herbicide mechanisms of action for POST annual bluegrass, and residual smooth crabgrass control. Flumioxazin at 0 or 0.42 kg ai ha^{-1} was evaluated in combination with flazasulfuron at 0.05 kg ai ha^{-1}, glufosinate at 1.26 kg ai ha^{-1}, glyphosate at 0.42 kg ae ha^{-1}, mesotrione at 0.28 kg ai ha^{-1}, pronamide at 1.68 kg ai ha^{-1}, or simazine at 1.12 kg ai ha^{-1}. All tank-mixtures improved POST annual bluegrass control from flumioxazin alone at 8 WAT, and controlled annual bluegrass ≥70% and ≥80% in 2012 and 2013, respectively. In 2012, flumioxazin tank-mixtures with flazasulfuron, glufosinate, glyphosate, and pronamide reduced time to control annual bluegrass 50% by ≥2 weeks from flumioxazin alone. However, no tank-mixture significantly reduced the time to achieve 50% control in 2013. Treatments that included flumioxazin provided excellent (90 to 100%) control of smooth crabgrass at 4, 5, and 6 months after treatment (MAT) in both years. Overall, tank-mixing flumioxazin with other herbicide chemistries may improve POST annual bluegrass control compared to exclusive treatments, and also provide excellent PRE smooth crabgrass control.

Introduction

Annual bluegrass (*Poa annua* L.) is a winter annual weed that reduces aesthetics and functionality of turfgrasses. Annual bluegrass has a bunch-type growth habit, light green color, and abundant seedhead production (Lush 1989; Sweeney and Danneberger 1997). Annual bluegrass decline in spring may further reduce turf quality and predispose areas to establishment of summer annuals, such as smooth crabgrass (*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl) (Johnson 1996; Tae-Joon et al. 2002).

Postemergence (POST) herbicides are often required to control established annual bluegrass in turf. However, annual bluegrass has developed resistance to several herbicide chemistries including glyphosate, sulfonylureas, and triazines (Brosnan et al. 2012; Cross et al. 2013; Darmency and Gasquez 1981; Heap 1997). Herbicides with these mechanisms of action have been repeatedly used due to cost effectiveness or tolerance of desirable turfgrasses. Utilizing herbicides with different mechanisms of action is necessary to combat resistance of annual bluegrass populations in long-term management.

Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor that offers an alternative mechanism of action for POST annual bluegrass control in bermudagrass (*Cynodon dactylon* (L.) Pers.) (Flessner et al. 2013). There has been no documented annual bluegrass resistance to Protox inhibiting herbicides, and flumioxazin could effectively control biotypes resistant to other mechanisms of action. Other Protox inhibitors used in turfgrass include carfentrazone, oxadiazon, and sulfentrazone. However, none of these herbicides provide POST annual bluegrass control at registered rates (Isgrigg et al. 2002; Senseman 2007; Toler et al. 2003). Flumioxazin has also shown preemergence (PRE) control of smooth crabgrass, and has important implications for PRE and POST weed control in turfgrass (McCullough et al. 2012).

In the Southern United States, flumioxazin may provide significant control of annual bluegrass with early winter treatments, but efficacy is reduced in late winter on mature annual bluegrass (Flessner et al. 2013; McCullough et al. 2012). Flessner et al. (2013) reported annual bluegrass with two tillers or less was controlled ≥95% with flumioxazin applications at 0.43 kg ai ha^{-1}, but annual bluegrass with four to six tillers was controlled <50%. Flumioxazin efficacy may be enhanced when tank-mixed with POST herbicides on mature annual bluegrass to provide more effective control in winter. The objective of this research was to evaluate tank-mixtures of flumioxazin with other herbicide mechanisms of action for POST annual bluegrass in winter, and residual smooth crabgrass control in spring.

Materials and Methods

Field experiments were conducted in Griffin, GA (33.26°N, 84.28°W), from February through August in 2012 and 2013. Soil was a Cecil sandy clay loam soil (fine, kaolinitic, thermic Typic Kanhapludults) with 2.5% organic matter and a pH of 6.0. Experiments were conducted on 'Tifway' bermudagrass that was mowed during active growth with reel-mowers at 1.6 cm two days per week. The field had clippings returned and was irrigated as needed to prevent turf wilting. Plots in 2013 were adjacent to plots in 2012. Bermudagrass was completely dormant on the day of treatments in both years.

Flumioxazin (SureGuard® 51WG, Valent U.S.A. Corporation, Walnut Creek, CA) at 0 or 0.42 kg ai ha^{-1} was evaluated in combination with six herbicides including: flazasulfuron (Katana 25DF, PBI Gordon Corporation, Kansas City, MO) at 0.05 kg ai ha^{-1}, glufosinate (Finale 1SC, Bayer CropScience, Kansas City, MO) at 1.26 kg ai ha^{-1}, glyphosate (isopropylamine, Roundup Pro 4SL, Monsanto Co., St. Louis, MO) at 0.42 kg ae ha^{-1}, mesotrione (Tenacity 4SC, BASF Corporation, Research Triangle Park, NC) at 0.28 kg ai ha^{-1}, pronamide (Kerb 50WP, Rohm and Haas, Philadelphia, PA) at 1.68 kg ai ha^{-1}, and simazine (Princep 4L, Syngenta Crop Protection, LLC, Greensboro, NC) at 1.12 kg ai ha^{-1}. Treatments included a nonionic surfactant (Chem Nut 80-20. Chem Nut Inc., Albany, GA) at 0.25% v/v, except for exclusive pronamide and simazine applications. Treatments were made February 29 in 2012 and February 28 in 2013 with a CO_2-pressured backpack sprayer calibrated to deliver 374 L ha^{-1} with a single 9504E flat-fan nozzle (Tee Jet, Spraying Systems Co., Roswell, GA).

Experimental design was a randomized complete block with four replications of 1 x 3-m plots. Bermudagrass injury was visually measured at 2, 3, 4, and 6 WAT on a percent scale where 0 equaled no injury and 100 equaled completely dead turf. Annual bluegrass and smooth crabgrass control was visually rated on a percent scale where 0 equaled no control and 100 equaled complete control. Visual ratings were taken 1, 2, 3, 4, 5, 6, 7 and 8 WAT for annual bluegrass control. Evaluations for smooth crabgrass control were made 4, 5, and 6 months after treatment (MAT). Smooth crabgrass cover was taken with grid counts on August 28 in 2013, and presented as a percent reduction from the nontreated by replication. Two samples were taken in each plot and the sampling grid was 0.58-m^2 containing 36-12.7 x 12.7-cm grids.

Data were subjected to analysis of variance at the 0.05 probability level in SAS (SAS® Institute v. 9.3, Cary, NC). Year by treatment interactions were detected for annual bluegrass control and bermudagrass injury, and thus years are presented independently. Year by treatment interactions were not detected for smooth crabgrass control and, thus years are combined. Predicted time for treatments to control annual bluegrass 50% (C_{50}) was determined with nonlinear regression analysis using SigmaPlot (Systat Software Inc. SigmaPlot v. 11.0, San Jose, CA), with the equation: $y = a + bx + cx^2$, where y is percent control, and x is time in weeks.

Means of annual bluegrass predicted C_{50} values, bermudagrass injury, and smooth crabgrass control were separated using Fisher's Protected LSD Test at $\alpha = 0.05$.

Results and Discussion

Annual Bluegrass Control. On the day of application, annual bluegrass cover across all plots was 71% (±1) and 37% (±1) in 2012 and 2013, respectively (Table 5.1). Flumioxazin by herbicide interactions were detected for annual bluegrass control, and thus all treatments are presented. In 2012, flumioxazin alone required 4.5 weeks to obtain 50% annual bluegrass control. Flumioxazin in combination with flazasulfuron, glufosinate, glyphosate, or pronamide provided 50% annual bluegrass control in ≤2.0 weeks, and was significantly faster than flumioxazin alone. Flumioxazin alone controlled annual bluegrass 60% at 8 WAT, but all tank-mixtures provided ≥70% control (Figure 5.1). Glufosinate plus flumioxazin provided the greatest control of annual bluegrass, and reached 94% at 8 WAT. No other treatment provided >79% control. Flumioxazin provided greater annual bluegrass control than any other herbicide applied alone at 8 WAT, in 2012.

In 2013, flumioxazin alone required 2.6 weeks to achieve 50% control, and no tank-mixture improved speed of control (Table 5.1). Flumioxazin alone controlled annual bluegrass only 55% at 8 WAT, but tank-mixtures improved control to ≥80% (Figure 5.1). All flumioxazin tank-mixtures provide good (80 to 89%) to excellent (90 to 100%) annual bluegrass control, and flumioxazin in combination with flazasulfuron or simazine controlled annual bluegrass >95% at 8 WAT. Flumioxazin tank-mixtures with glufosinate or simazine controlled annual bluegrass 99% at 8 WAT, and provided the greatest control. All herbicides applied alone, except mesotrione, provided better control than flumioxazin alone at 8 WAT.

Tank-mixtures controlled annual bluegrass greater than or equal to exclusive herbicide applications on all evaluation dates in both years. Glufosinate was the only herbicide to provide more rapid annual bluegrass control than flumioxazin alone, and the combination with flumioxazin never increased speed of control. Bermudagrass was dormant on day of treatments, but greenup was detected at 2 WAT in 2012. Treatments that contained glufosinate or glyphosate caused unacceptable injury (>20%) to bermudagrass at 2 WAT (Table 5.2). Turf recovered with <20% injury at 3 WAT from all treatments. In 2013, there was no greenup observed until 3 WAT and injury was detected. No treatments caused unacceptable injury, but applications that included glufosinate caused ≥10% injury at 3 and 4 WAT. All other herbicides injured bermudagrass <10% in 2013. No injury was observed at 6 WAT in both years.

Turf managers may need to enhance speed of annual bluegrass control in late winter due to reduced efficacy compared to fall. Flessner et al. (2013) reported flumioxazin at 0.43 kg ai ha^{-1} controlled annual bluegrass 98% and 72% from November and February applications, respectively at 2 MAT. Tank-mixing flumioxazin with other herbicide mechanisms of action increased control from flumioxazin alone. Tank-mixing herbicides is a method that can effectively control resistant weeds, and increase weed control spectrum while reducing application rates (Beckie 2006; Green and Owen 2011). For example, tank-mixtures that include flumioxazin have been effectively used for PRE and POST weed control in cotton (*Gossypium hirsutum* L.), potato (*Solanum tuberosum* L.), and ornamentals (Kelly et al. 2006; Neve et al. 2011; Wehtje et al. 2010). In turfgrass, tank-mix partners may help flumioxazin overcome limitations from annual bluegrass maturity and low temperature.

Sulfonylureas and triazines are widely used for POST annual bluegrass control in warm-season turfgrasses. Sulfonylureas, such as flazasulfuron, inhibit the acetolactate synthase (ALS) enzyme in the biosynthesis of branched-chain amino acids (LaRossa and Schloss 1984). Triazines, such as simazine, are photosystem II inhibitors that are frequently used for controlling annual bluegrass and other winter annual weeds (Darmency and Gasquez 1981; Johnson 1980; Perry et al. 2012). Flazasulfuron and simazine improved control of annual bluegrass in tank-mixtures with flumioxazin, compared to flumioxazin alone, at 8 WAT in both years. Although, flazasulfuron and simazine have potential to enhance flumioxazin efficacy, annual bluegrass, resistance to these chemistries has been reported (Cross et al. 2013; Hanson and Mallory-Smith 2000; Kelly et al. 1999; Cross et al. 2013; McElroy et al. 2013; Perry et al. 2012). Tank-mixtures of flumioxazin with flazasulfuron or simazine may improve control in areas with suspected resistance to these mechanisms of action, and warrant further investigation.

Glufosinate and glyphosate are nonselective herbicides that may effectively control annual bluegrass in dormant bermudagrass (Binkholder et al. 2011; Johnson and Ware 1978; Toler et al. 2007). Glufosinate is a glutamine synthetase inhibitor with no reported annual bluegrass resistance (Flessner et al. 2013; McElroy et al. 2013). Glyphosate inhibits 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme in the shikimic acid pathway during aromatic amino acid synthesis (Amrhein 1980; Baerson et al. 2002). Glyphosate can provide practitioners with an economical, broad-spectrum weed control option, but overuse has resulted in the spread of resistant populations (Binkholder et al. 2011; Brosnan et al. 2012). Glufosinate or glyphosate tank-mixed with flumioxazin appear to enhance control of mature annual bluegrass from flumioxazin alone. Bermudagrass injury may concern turf managers from glufosinate or glyphosate use in spring, and could increase susceptibility to disease, environmental stresses, or invasion of weeds not controlled by these herbicides.

Mesotrione is a *p*-hydroxyphenylpyruvate dioxygenase (HPPD) inhibiting herbicide that causes bleaching in susceptible plants followed by necrosis (Lee et al. 1997; Mitchell et al. 2001). Mesotrione may control seedling annual bluegrass, but has inconsistent efficacy for controlling tillered populations (Reicher et al. 2011; Skelton et al. 2012). However, mesotrione increased efficacy of other herbicides including acetochlor, amicarbazone, and atrazine for POST annual bluegrass control in tank-mixtures (Armel et al. 2009; Elmore et al. 2013). Mesotrione alone provided <40% annual bluegrass control, but tank-mixtures with flumioxazin provided ≥70% control in both years.

Pronamide is a benzamide that disrupts mitosis by inhibiting polymerization of microtubules in susceptible species (Carlson et al. 1975; Vaughn and Lehnen 1991; Vaughan and Vaughn 1987). Pronamide controls annual bluegrass with PRE and POST applications, and is safe in most major warm-season grasses (McCullough et al. 2012). A limitation to pronamide use is speed of annual bluegrass control that could be improved by tank-mix partners. Pronamide in combination with flumioxazin enhanced annual bluegrass control compared to both herbicides alone, and has promising implications for resistance management.

Providing rapid control of actively growing annual bluegrass in dormant bermudagrass may be advantageous in preventing weed establishment and maintaining turf density (Bingham et al. 1969; Johnson 1980). No herbicide chemistry was antagonistic with flumioxazin, and it appears tank-mixtures of flumioxazin with flazasulfuron, glufosinate, glyphosate, or pronamide have potential to enhance speed of control from flumioxazin applied alone. Tank-mixing with other herbicides may help overcome the limitations of flumioxazin efficacy on controlling mature annual bluegrass.

Smooth Crabgrass Control. Smooth crabgrass cover increased in nontreated plots from May to August, and measured 30% (±12) and 28% (±3) at 6 MAT in 2012 and 2013, respectively (Table 5.3). Flumioxazin by herbicide interactions were not detected for smooth crabgrass control, and thus, main effects are presented. Treatments that included flumioxazin provided ≥95% smooth crabgrass control on all evaluation dates, and reduced grid counts 84% from the nontreated at 6 MAT. Treatments without flumioxazin provided ≤25% smooth crabgrass control, and had 21% grid count reductions at 6 MAT from nontreated.

None of the herbicides antagonized flumioxazin efficacy on smooth crabgrass and control was similar to previous research. McCullough et al. (2012) and Warren et al. (2013) reported flumioxazin at 0.42 kg ai ha^{-1} had >80% smooth crabgrass control in September from March applications. Late winter application of flumioxazin may effectively control smooth crabgrass similar to another Protox inhibitor, oxadiazon. McCurdy et al. (2008) noted oxadiazon at 4.48 kg ha^{-1}, provided >90% smooth crabgrass control at 5 MAT from March applications. Johnson (1976) noted similar PRE crabgrass control from oxadiazon at 4.50 kg ha^{-1}. There is limited reporting in scientific literature on flumioxazin use for PRE smooth crabgrass control, but late winter applications could provide six months of control in turfgrass.

Conclusion

Flumioxazin offers an alternative mechanism of action for POST annual bluegrass control with residual crabgrass control in turf. Utilizing herbicides with different mechanisms of action, such as flumioxazin, could help prevent herbicide resistance of annual bluegrass in turfgrass. Flumioxazin may provide significant POST control, but annual bluegrass maturity may reduce efficacy of winter applications. Tank-mixing flumioxazin with flazasulfuron, glufosinate, glyphosate, and pronamide improved speed of annual bluegrass control compared to flumioxazin alone in at least one of two years. Late winter applications of flumioxazin also provided excellent PRE smooth crabgrass control, but tank-mixing other herbicides did not improve residual control. Further research is needed to evaluate efficacy of these combinations on POST annual bluegrass control of populations with suspected herbicide resistance. Research is also warranted on rates of tank-mix partners with flumioxazin to determine the benefits for annual bluegrass control and bermudagrass safety.

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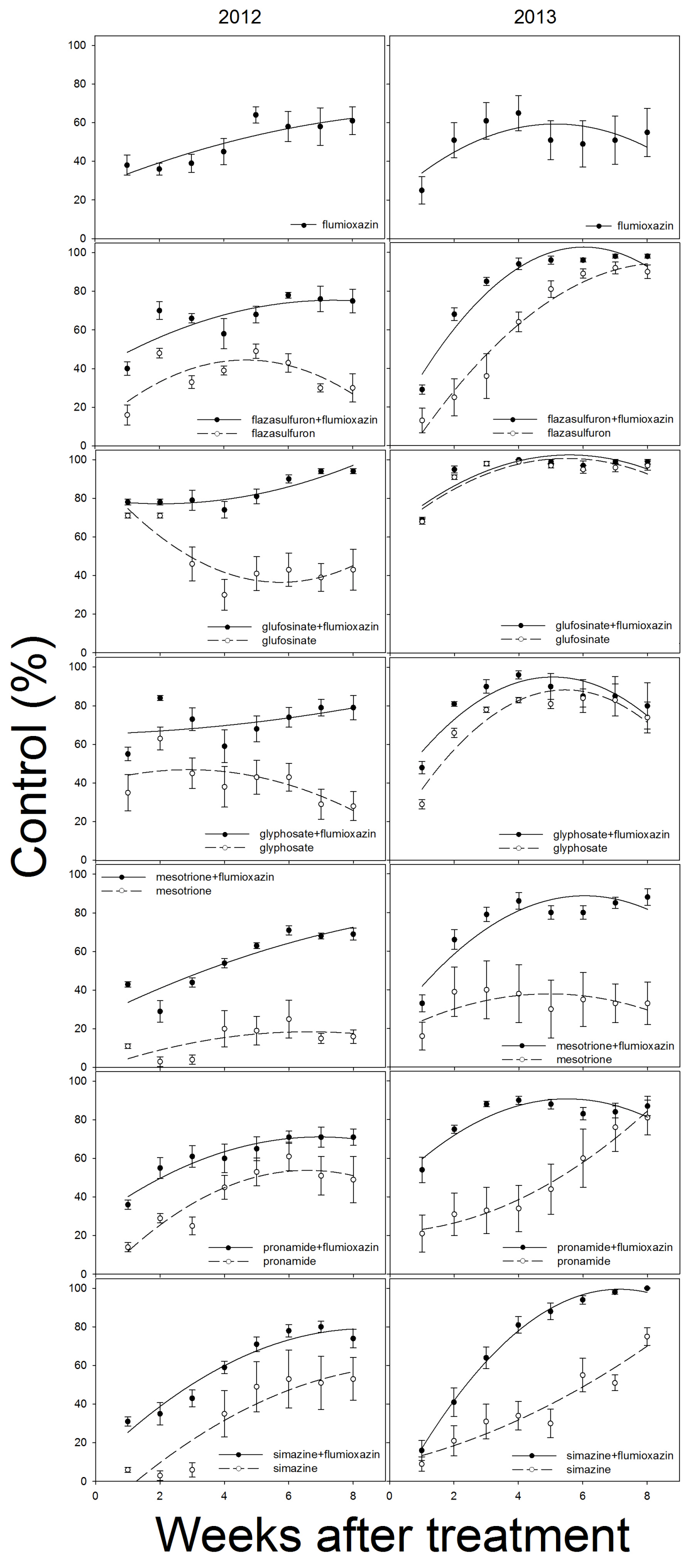

Figure 5.1. Annual bluegrass control following flumioxazin applications with various tank-mix partners in field experiments, 2012-2013, Griffin, GA. Error bars represent standard error of the mean. Nonlinear regression equations in Table 5.1.

Table 5.1. Predicted time in weeks required for flumioxazin applications with various tank-mix partners to provide 50% control (C_{50}) of annual bluegrass in field experiments, 2012-2013, Griffin, GA.

Treatment[a]	Rate	C_{50} 2012	C_{50} 2013
	kg ai ha^{-1}	weeks	
flumioxazin	0.42	4.5	2.6
flazasulfuron	0.05	>8.0	3.2
glufosinate	1.26	<1.0	<1.0
glyphosate	0.42[c]	>8.0	1.6
mesotrione	0.28	>8.0	>8.0
pronamide	1.68	4.9	5.3
simazine	1.12	6.5	5.7
flazasulfuron + flumioxazin	0.05 + 0.42	1.2	1.5
glufosinate + flumioxazin	1.26 + 0.42	<1.0	<1.0
glyphosate + flumioxazin	0.42 + 0.42	<1.0	<1.0
mesotrione + flumioxazin	0.28 + 0.42	3.4	1.5
pronamide + flumioxazin	1.68 + 0.42	2.0	<1.0
simazine + flumioxazin	1.12 + 0.42	3.0	2.4
	$LSD_{0.05}$	2.0	2.3
	Equations[b]		
flumioxazin	0.42	$y = 26.83 + 6.68x + 0.34x^2$ $r^2 = 0.38$; SE = 12.76	$y = 20.38 + 15.22x - 1.48x^2$ $r^2 = 0.12$; SE = 22.98
flazasulfuron	0.05	$y = 9.84 + 14.58x - 1.56x^2$ $r^2 = 0.29$; SE = 10.71	$y = -18.91 + 26.75x - 1.58x^2$ $r^2 = 0.85$; SE = 13.14
glufosinate	1.26	$y = 92.79 - 19.53x + 1.68x^2$ $r^2 = 0.39$; SE = 15.29	$y = 61.28 + 14.34x - 1.30x^2$ $r^2 = 0.70$; SE = 5.86
glyphosate	0.42	$y = 40.20 + 4.50x - 0.80x^2$ $r^2 = 0.16$; SE = 16.92	$y = 10.92 + 28.30x - 2.60x^2$ $r^2 = 0.74$; SE = 10.23
mesotrione	0.28	$y = -0.76 + 5.65x - 0.42x^2$ $r^2 = 0.13$; SE = 12.93	$y = 16.21 + 8.75x - 0.89x^2$ $r^2 = 0.02$; SE = 30.01
pronamide	1.68	$y = -5.02 + 17.89x - 1.36x^2$ $r^2 = 0.48$; SE = 15.55	$y = 22.28 + 0.21x + 0.95x^2$ $r^2 = 0.41$; SE = 25.82
simazine	1.12	$y = -18.30 + 15.54x - 0.77x^2$ $r^2 = 0.45$; SE = 23.15	$y = 8.04 + 3.87x + 0.60x^2$ $r^2 = 0.72$; SE = 13.83
flazasulfuron + flumioxazin	0.05 + 0.42	$y = 39.73 + 9.43x - 0.63x^2$ $r^2 = 0.40$; SE = 11.82	$y = 7.81 + 31.39x - 2.60x^2$ $r^2 = 0.91$; SE = 7.08
glufosinate + flumioxazin	1.26 + 0.42	$y = 78.55 - 1.94x + 0.53x^2$ $r^2 = 0.58$; SE = 6.20	$y = 63.25 + 14.10x - 1.27x^2$ $r^2 = 0.70$; SE = 5.79
glyphosate + flumioxazin	0.42 + 0.42	$y = 65.42 + 0.29x - 0.17x^2$ $r^2 = 0.10$; SE = 13.46	$y = 34.63 + 23.72x - 2.34x^2$ $r^2 = 0.39$; SE = 16.16
mesotrione + flumioxazin	0.28 + 0.42	$y = 25.16 + 8.33x - 0.31x^2$ $r^2 = 0.72$; SE = 8.37	$y = 20.78 + 22.61x - 1.88x^2$ $r^2 = 0.72$; SE = 10.32
pronamide + flumioxazin	1.68 + 0.42	$y = 29.22 + 12.00x - 0.86x^2$ $r^2 = 0.56$; SE = 9.94	$y = 44.46 + 16.59x - 1.50x^2$ $r^2 = 0.60$; SE = 8.52
simazine + flumioxazin	1.12 + 0.42	$y = 10.18 + 16.19x - 0.95x^2$ $r^2 = 0.81$; SE = 8.69	$y = -11.51 + 30.99x - 2.17x^2$ $r^2 = 0.93$; SE = 8.32

[a]Products applied were SureGuard® 51WG (flumioxazin) Valent U.S.A. Corporation, Walnut Creek, CA; Katana 25DF (flazasulfuron), PBI Gordon Corporation, Kansas City, MO; Finale 1SC (glufosinate), Bayer CropScience, Kansas City, MO; Roundup Pro 4SL (glyphosate isopropylamine), Monsanto Co., St. Louis, MO; Tenacity 4SC (mesotrione), BASF Corporation, Research Triangle Park, NC; Kerb 50WP (pronamide), Rohm and Haas, Philadelphia, PA; Princep 4L (simazine), Syngenta Crop Protection, LLC, Greensboro, NC.

[b]Nonlinear regression analysis using polynomial, quadratic equation: $y = a + bx + cx^2$ where y is control from the nontreated expressed as a percentage, a, b, and c are constants, and x is time in weeks.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$.

[c]Glyphosate rate in kg ae ha^{-1}.

Applications were made February 29 in 2012 and February 28 in 2013.

Table 5.2. 'Tifway' bermudagrass injury from flumioxazin applications with various tank-mix partners in field experiments, 2012-2013, Griffin, GA.

Year		2012			2013		
		Injury (WAT[a])					
Treatment[b]	Rate	2	3	4	2	3	4
	kg ai ha^{-1}	%					
flumioxazin	0.42	9	3	3	0	0	0
flazasulfuron	0.05	0	0	0	0	0	0
glufosinate	1.26	50	10	4	0	10	18
glyphosate	0.42[c]	30	10	5	0	0	0
mesotrione	0.28	0	0	0	0	0	1
pronamide	1.68	0	0	1	0	0	0
simazine	1.12	0	1	3	0	0	0
flazasulfuron + flumioxazin	0.05 + 0.42	3	1	3	0	0	0
glufosinate + flumioxazin	1.26 + 0.42	54	9	6	0	10	19
glyphosate + flumioxazin	0.42 + 0.42	58	13	5	0	5	6
mesotrione + flumioxazin	0.28 + 0.42	6	3	5	0	0	0
pronamide + flumioxazin	1.68 + 0.42	14	4	4	0	0	0
simazine + flumioxazin	1.12 + 0.42	3	0	0	0	0	0
	$LSD_{0.05}$	9	6	7	0	2	3
Flumioxazin		*	NS	NS	NS	*	NS
Herbicide		*	*	NS	NS	*	*
Flumioxazin*Herbicide		*	NS	NS	NS	*	*

[a]WAT = weeks after treatment.

[b]Products applied were SureGuard® 51WG (flumioxazin) Valent U.S.A. Corporation, Walnut Creek, CA; Katana 25DF (flazasulfuron), PBI Gordon Corporation, Kansas City, MO; Finale 1SC (glufosinate), Bayer CropScience, Kansas City, MO; Roundup Pro 4SL (glyphosate isopropylamine), Monsanto Co., St. Louis, MO; Tenacity 4SC (mesotrione), BASF Corporation, Research Triangle Park, NC; Kerb 50WP (pronamide), Rohm and Haas, Philadelphia, PA; Princep 4L (simazine), Syngenta Crop Protection, LLC, Greensboro, NC.

[c]Glyphosate rate in kg ae ha^{-1}.

Applications were made February 29 in 2012 and February 28 in 2013.

Means were separated with Fisher's Protected LSD Test at $\alpha = 0.05$.

LSD = least significant difference; * = significant; NS = not significant.

Table 5.3. Smooth crabgrass control and cover reductions from nontreated following flumioxazin applications with various tank-mix partners in combined field experiments, 2012-2013, Griffin, GA.

Treatment[c]	Rate	Control (MAT[a])			Cover Reductions[b] (MAT)
		4	5	6	6
	kg ai ha^{-1}	%			
Flumioxazin	0	25	23	25	21
	0.42	97	96	95	84
	$LSD_{0.05}$	10	9	10	10
Tank-mix Herbicide[d]					
flazasulfuron	0.05	62	63	62	65
glufosinate	1.26	52	55	54	47
glyphosate	0.42[e]	58	54	58	44
mesotrione	0.28	62	62	61	58
pronamide	1.68	73	66	68	51
simazine	1.12	61	59	59	57
	$LSD_{0.05}$	19	17	19	19
Flumioxazin		*	*	*	*
Herbicide		NS	NS	NS	NS
Flumioxazin*Herbicide		NS	NS	NS	NS

[a]MAT = months after treatment.

[b]In 2013, two samples were taken in each plot with a 0.58-m^2 grid comprised of 36-12.7 x 12.7-cm grids.

[c]Products applied were SureGuard® 51WG (flumioxazin) Valent U.S.A. Corporation, Walnut Creek, CA; Katana 25DF (flazasulfuron), PBI Gordon Corporation, Kansas City, MO; Finale 1SC (glufosinate), Bayer CropScience, Kansas City, MO; Roundup Pro 4SL (glyphosate isopropylamine), Monsanto Co., St. Louis, MO; Tenacity 4SC (mesotrione), BASF Corporation, Research Triangle Park, NC; Kerb 50WP (pronamide), Rohm and Haas, Philadelphia, PA; Princep 4L (simazine), Syngenta Crop Protection, LLC, Greensboro, NC.

[d]Evaluated with flumioxazin at 0 and 0.42 kg ai ha^{-1}.

[e]Glyphosate rate in kg ae ha^{-1}.

Applications were made February 29 in 2012 and February 28 in 2013. Smooth crabgrass cover was 30% (±12) and 28% (±3) in 2012 and 2013, respectively, in nontreated plots at 6 MAT.

Means were separated with Fisher's Protected LSD Test at α = 0.05.

LSD = least significant difference; * = significant; NS = not significant.

CHAPTER 6

OVERALL CONCLUSIONS

Postemergence (POST) herbicides are often required to control established annual bluegrass (*Poa annua* L.) in turf. However, annual bluegrass has developed resistance to several herbicide chemistries. Utilizing herbicides with different mechanisms of action is necessary to prevent resistance of annual bluegrass populations in long-term management. Flumioxazin is a protoporphyrinogen oxidase (Protox) inhibitor that offers an alternative mechanism of action to other chemistries for POST annual bluegrass control in bermudagrass (*Cynodon dactylon* (L.) Pers.). Flumioxazin has also shown preemergence (PRE) control of summer annual grassy weeds, and has important implications for PRE and POST weed control in turfgrass.

Maximizing flumioxazin efficacy is critical for its utilization in warm-season turfgrass weed control programs. Temperature and application placement affect flumioxazin efficacy for annual bluegrass and large crabgrass (*Digitaria sanguinalis* (L.) Scop.) control. Flumioxazin caused more rapid injury to annual bluegrass and large crabgrass as temperatures increased from 10 to 30° C. Practitioners may fail to control annual bluegrass during winter months due to reduced efficacy on mature annual bluegrass and cold temperatures compared to late fall timings. In greenhouse experiments, soil-only and soil-plus-foliar applications of flumioxazin resulted in >10% injury of both species than foliar-only applied treatments. Results suggest root uptake is critical for maximizing flumioxazin efficacy for annual bluegrass and large crabgrass control in turfgrass.

Flumioxazin is currently labeled for dormant bermudagrass only due to injury concerns during active growth, but treatments have potential for use in other warm-season turfgrasses. Late winter applications caused minimal injury to bermudagrass, seashore paspalum (*Paspalum vaginatum* Sw.), St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze), and zoysiagrass (*Zoysia matrella* (L.) Merr.). Centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.) injury from late winter timings was inconsistent over years, but results suggest injury may be substantial at late spring timings. Flumioxazin may be applicable for controlling annual bluegrass in bermudagrass and other warm-season turfgrasses with late winter applications with minimal (<20%) green cover. Flumioxazin may have an extended period of safety on warm-season turfgrasses during years of delayed greenup due to low temperatures, but all turfgrasses may be injured during active growth. Bermudagrass, seashore paspalum, St. Augustinegrass, and zoysiagrass may recover from flumioxazin injury after greenup, but centipedegrass appears potentially sensitive at all timings. Results advocate expanding the current turfgrass label for flumioxazin use in dormant seashore paspalum and zoysiagrass. St. Augustinegrass may also be tolerant, but there is risk of injury if turf has >20% green cover at application. Further research is warranted to determine if granular formulations could minimize turfgrass injury compared to sprayable treatments. Currently, oxadiazon is labeled in sprayable formulations to dormant warm-season turf, but only granular formulations may be used after greenup. Perhaps granular formulations of flumioxazin could be safely applied after turf greenup for weed control, and warrants further investigation.

Flumioxazin has potential for POST annual bluegrass control, but low temperatures and annual bluegrass maturity may influence winter applications. Applications in winter or spring could reduce herbicide use in turf by providing residual summer annual weed control.

Flumioxazin appears effective for PRE smooth crabgrass (*Digitaria ischaeum* (Schreb.) Schreb. ex Muhl.) control, and may control other summer annual weeds when used for POST annual bluegrass control in winter. Overall, adjuvants did not enhance speed of annual bluegrass control, but flumioxazin-only treatments controlled annual bluegrass >80%, and provided four to six months of >80% PRE smooth crabgrass control.

Utilizing herbicides with different mechanisms of action, such as flumioxazin, could help prevent herbicide resistance of annual bluegrass in turfgrass. Flumioxazin may provide significant POST control, but annual bluegrass maturity may reduce efficacy of winter applications. Tank-mixing flumioxazin with flazasulfuron, glufosinate, glyphosate, and pronamide improved speed of annual bluegrass control compared to flumioxazin alone in at least one of two years. Late winter applications of flumioxazin also provided excellent PRE smooth crabgrass control, but tank-mixing other herbicides did not improve residual control.

Flumioxazin has potential to be an effective tool in turf weed control programs. Flumioxazin may provide POST annual bluegrass and PRE smooth crabgrass control in bermudagrass and other warm-season turfgrasses with late winter applications. Flumioxazin may help combat annual bluegrass resistance, and limit the use of other herbicides for PRE summer annual weed control.