Evaluation of Flumioxazin as a Weed Management Tool in Warm-Season Turfgrass Systems

by

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Abstract

Weed management in warm-season turfgrass has been complicated by two converging developments: the confirmation of acetolactate synthase (ALS) inhibitor-resistant *Kyllinga* (Cyperaceae) populations and increasing regulatory restriction of oxadiazon, a protoporphyrinogen oxidase (PPO)-inhibiting herbicide long relied upon for weed control in managed turf. Flumioxazin, a PPO-inhibiting herbicide with a broader spectrum of activity than oxadiazon and no known cross-resistance with ALS-inhibiting chemistries, has emerged as a candidate to address both challenges. This work evaluated the efficacy, application biology, and resistance-management utility of flumioxazin across complementary field and greenhouse studies in warm-season turfgrass systems.

Field experiments conducted at the Auburn University Sports Surface Field Laboratory and Brundidge Country Club evaluated granular flumioxazin (StayGuard, 0.42 kg ai ha^{-1}) for preemergence weed control in bermudagrass (*Cynodon dactylon* [L.] Pers.). A single spring application of granular flumioxazin provided season-long cockscomb kyllinga (*Kyllinga squamulata*) control comparable to indaziflam and significantly superior to prodiamine or pendimethalin applied alone, while sequential programs pairing a conventional preemergence herbicide with a follow-up flumioxazin application consistently achieved the highest levels of broad-spectrum control. Granular flumioxazin also provided commercially acceptable suppression (>85%)of smooth crabgrass (*Digitaria ciliaris*) and contributed to enhanced bermudagrass color through its fertilizer carrier. However, residual grass control from a single flumioxazin application declined throughout the season, and flumioxazin was not a reliable

standalone tool for annual bluegrass (*Poa annua*) suppression in dormant bermudagrass, which required postemergence herbicide partners to achieve complete control.

Complementary greenhouse experiments characterized the resistance status of field-collected *Kyllinga* populations and investigated the mechanism underlying flumioxazin activity. An initial screening of four populations (Missouri, New Jersey, Auburn, and Brundidge) revealed a spectrum of ALS inhibitor resistance, including complete cross-resistance across three ALS inhibitor subclasses in the Auburn population and a class-specific resistance phenotype in the New Jersey population not previously documented in *Kyllinga*, which remained susceptible to trifloxysulfuron while exhibiting partial to complete resistance to sulfonylurea and imidazolinone subclasses. Across all four populations, the PPO inhibitors sulfentrazone and flumioxazin provided 75 to 100% control regardless of ALS resistance mechanism, and subsequent dose-response assays confirmed the absence of cross-resistance, with all populations susceptible to flumioxazin at or above its labeled rate. A soil-foliar response study using a perlite barrier and subirrigation methodology demonstrated that foliar contact, rather than soil or root uptake, is the dominant pathway for flumioxazin activity against Kyllinga species, with foliar-applied and combined foliar-plus-soil treatments achieving 97 to 100% control compared to only 4 to 24% control from granular delivery. Doveweed (*Murdannia nudiflora*) responded differently, achieving 73% control from granular flumioxazin, a divergence attributed to its shallow, fibrous root system.

Collectively, these findings establish flumioxazin as an effective and mechanistically distinct alternative to ALS-inhibiting herbicides for *Kyllinga* management and a viable successor to oxadiazon in warm-season turfgrass weed control programs. Liquid foliar applications are recommended when *Kyllinga* control is the primary objective, while granular formulations are best suited to preemergence use ahead of *Kyllinga* emergence or to doveweed-dominant weed communities. These results provide turfgrass managers and industry partners with practical, mechanistically grounded guidance for integrating flumioxazin into resistance-management programs targeting *Kyllinga* and other key weed species in bermudagrass turf.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this thesis, the following Artificial Intelligence (AI) tools were used: ChatGPT. These tools were used primarily to troubleshoot statistical code, provide example analysis scripts, and identify areas that require improved clarity. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain scholarly integrity of this research.

Digital Accessibility Disclosure

In the preparation of this thesis, the following digital accessibility tools were used to ensure this document complies with federal requirements: Microsoft Word Accessibility Checker. The author acknowledges full responsibility for the intellectual content of this work and has made a good faith effort to comply with digital accessibility requirements in publishing, wherein the nature of the content does not significantly change in order to do so. Furthermore, all content has been reviewed and revised to meet these requirements prior to final publication.

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List of Abbreviations

ai	active ingredient
ALS	acetolactate synthase
ANOVA	analysis of variance
CI	confidence interval
CRD	completely randomized design
DAIA	days after initial application
DAT	days after treatment
EPA	United States Environmental Protection Agency
GR50	herbicide dose required to reduce shoot biomass by 50% relative to the nontreated control
LL.4	four-parameter log-logistic model
LSD	least significant difference
MSMA	monosodium methanearsonate
POST	postemergence
PPO	protoporphyrinogen oxidase
RCBD	randomized complete block design
RF	resistance factor
ROS	reactive oxygen species
SAS	Statistical Analysis System
SE	standard error

WSSA	Weed Science Society of America

Chapter 1 Literature Review

Introduction

Turfgrass is defined as a plant system that remains green for 6 or more months while maintaining a dense contiguous ground cover during dormancy (Steinke & Ervin, 2013). Turfgrass environments, encompassing golf courses, sports fields, sod farms, and residential and commercial lawns, demand exceptionally high aesthetic and functional standards, leaving little tolerance for weed pressure. Herbicides have long served as the primary tool for maintaining acceptable turfgrass quality, but the continued reliance on a limited number of mode-of-action chemistries has created pressure for the selection and spread of herbicide-resistant weed biotypes. Among the most problematic weed complexes emerging in managed turfgrass is the genus *Kyllinga*, a group of sedge weeds in the family Cyperaceae. The recent confirmation of acetolactate synthase (ALS) inhibitor-resistant green kyllinga (*Kyllinga brevifolia*) has fundamentally altered the management for superintendents who have historically relied on ALS-inhibiting herbicides for selective *Kyllinga* control (Westbury et al., 2022).

Concurrent with growing resistance concerns, turfgrass managers have faced regulatory and market pressures that have affected the availability of legacy herbicide chemistries. Oxadiazon, a protoporphyrinogen oxidase (PPO)-inhibiting herbicide with decades of established use in turfgrass, has faced increasing restrictions due to human health concerns. Flumioxazin, also a PPO-inhibitor but with a distinct chemical profile and a broader spectrum of activity, has emerged as a leading candidate to fill the market void left by oxadiazon's contraction. Beyond simple substitution, flumioxazin's activity profile raises the possibility that it could offer new avenues for managing weed species with established resistance to ALS-inhibiting chemistries, including resistant *Kyllinga* biotypes.

Taxonomy and Ecology of *Kyllinga* in Turfgrass Systems

The genus *Kyllinga* belongs to the family Cyperaceae and has historically been subject to significant taxonomic uncertainty. Bryson et al. (1997) provided one of the foundational treatments of *Kyllinga* as a genus of neglected weeds in the continental United States, noting that these plants were long overlooked relative to their relatives in *Cyperus*. The photosynthesis biology of Cyperaceae is relevant to both the competitive ecology of *Kyllinga* species and their physiological responses to herbicides. Bruhl and Wilson (2007) conducted a comprehensive survey of C3 and C4 photosynthetic pathways across Cyperaceae, finding that the family contains representatives of both pathways and that C4 photosynthesis has evolved multiple times independently within the family. The predominant *Kyllinga* species found in turfgrass: *K. breviofolia*, *K. gracillima*, *K. squamulata*, and *K. pumila*, are C4 plants, a metabolic characteristic that confers a significant competitive advantage in the warm-season growing conditions typical of the transitional and southern turfgrass zones of the United States (Bruhl and Wilson, 2007). The C4 syndrome in these species contributes to high water-use efficiency, reduced photorespiration, and robust growth during the summer months when turfgrass managers most often observe *Kyllinga* infestations expanding aggressively.

McElroy at al. (2005) undertook a systematic assessment of the habitat preferences and distribution of green kyllinga (*K. brevifolia*) and false-green kyllinga (*K. gracillima*) within turfgrass systems, providing data for understanding where and why these weeds establish. Their survey of golf course fairways and roughs across North Carolina revealed that elevation and edaphic factors played significant roles in delineating the habitat of the two species. Green kyllinga was more frequently associated with wetter, lower-lying areas and soils with higher moisture retention, while false-green kyllinga occupied drier, higher-elevation areas within the same sites. These habitat preferences reflect the broader ecological tolerance ranges of the two species and have direct implications for site-specific weed management strategies.

The distinction between green and false-green kyllinga has important practical consequences because the two species can appear morphologically similar to the untrained observer but differ in their ecological behavior, seed germination requirements, and responses to herbicide treatments. Lowe et al. (1999) examined seed germination of *K. brevifolia*, *K. squamulata*, and *K. pumila* in controlled environments, finding significant differences in the germination responses of those species to temperature, light, and nitrate availability. *Kyllinga brevifolia* germinated most freely under warm temperatures and responded positively to nitrate, suggesting that fertilized, actively managed turfgrass sites provide conditions conducive to recruitment from seed. However, *Kyllinga* species also spread vigorously through vegetative propagation via rhizomes and stolons, and the reproductive contributions of seed versus vegetative spread in field populations remains incompletely understood.

Cockscomb kyllinga (*K. squamulata*) is distinguished among the turfgrass *Kyllinga* complex by its particularly aggressive seedling establishment. Bunnel et al. (2001) documented that cockscomb kyllinga infests turf through immense seedling establishment, a characteristic that distinguishes its population dynamics from the more rhizome-dominated spread of green and false-green kyllinga, which makes preemergence herbicide programs especially important for its management. The co-occurrence of *Kyllinga* with other problematic warm-season weeds, including doveweed (*Murdannia nudiflora* [L.] Brenan), a summer annual broadleaf that grows into dense mats capable of outcompeting turfgrass (Atkinson et al., 2019), and smooth crabgrass (*Digittaria ischaemum* [Schreb.] Schreb. Ex Muhl.), a summer annual grass for which herbicide resistance in turfgrass was first confirmed in 1996 (Heap, 2025), creates complex, multi-species weed management challenges in warm-season turfgrass systems. Effective management of these co-occurring weed species requires herbicide programs with broad-spectrum activity.

The competitive success of *Kyllinga* in managed turfgrass is attributable to several interacting factors. The C4 photosynthetic pathway provides a metabolic foundation for competitive dominance during warm-season growing conditions (Bruhl and Wilson, 2007). The rhizomatous and stoloniferous growth habit of *K. brevifolia* and *K. gracillima* enables these species to rapidly colonize disturbed or stressed turfgrass areas and to regenerate after partial defoliation by mowing. The species' tolerance of the low mowing heights typical of golf course fairways, often 12 to 19 mm, further enhances their persistence in highly managed settings. McElroy et al. (2005) noted that *Kyllinga* infestations were predominantly associated with high-traffic areas, shade, and sites with poor surface drainage, patterns consistent with the species moisture preferences and tolerance of mechanical disturbance. The combination of aggressive vegetative spread, warm-season vigor, and tolerance of intensive management practices makes *Kyllinga* one of the most persistent weed problems in southern turfgrass. These biological characteristics also mean that any disruption in effective herbicide control, including the emergence of herbicide resistance, can rapidly translate into widespread infestation.

Herbicide Management of *Kyllinga* in Turfgrass

Prior to the confirmation of ALS-resistant biotypes, chemical management of *Kyllinga* in turfgrass relied heavily on acetolactate synthase (ALS)-inhibiting herbicides, particularly the sulfonylureas halosulfuron-methyl and trifloxysulfuron-sodium, and the imidazolinone imazaquin. McElroy et al. (2004a) investigated the absorption, translocation, and metabolism of halosulfuron and trifloxysulfuron in both *K. brevifolia* and *K. gracillima*, finding that both herbicides were absorbed readily through foliar and root uptake pathways, though with differences in the relative efficiency of each pathway between the two species. Translocation was predominantly symplastic, with accumulation in meristematic tissues consistent with the ALS-inhibiting mechanism of action. Metabolic degradation of these herbicides was detected in both species, suggesting that some degree of metabolic tolerance exists even in susceptible populations, a finding with implications for the pace at which resistance could evolve under selection pressure.

McElroy et al. (2004b) compared foliar versus soil exposure of *K. brevifolia* and *K. gracillima* to postemergence treatments of halosulfuron, imazaquin, MSMA, and an experimental chemical (CGA-362622), finding that foliar exposure was generally more effective than soil exposure for ALS-inhibiting chemistries. This result reflects the importance of herbicide uptake through the leaf surface in the sedge control context and underscores the need for good spray coverage and appropriate adjuvant use in *Kyllinga* control programs. In a parallel study, McElroy et al. (2003) examined selective exposure of yellow nutsedge (*Cyperus esculentus*) and purple nutsedge (*Cyperus rotundus*)—close relatives of *Kyllinga*—to the same herbicide regimens, finding broadly similar patterns of response. Collectively, these studies established the efficacy of ALS-inhibiting herbicides for Cyperaceae management in turfgrass.

McElroy et al. (2005b) subsequently evaluated the performance of these herbicides under field conditions on golf course fairways and roughs, demonstrating that halosulfuron provided reliable control of green and false-green kyllinga when applied at label rates with appropriate timing relative to weed growth stage. Multiple applications were often required for season-long control, reflecting the continuous germination and vegetative regrowth characteristics of *Kyllinga* populations. Despite the need for repeated treatments, ALS-inhibiting herbicides remained the cornerstone of *Kyllinga* management in turfgrass for over two decades.

The landscape of *Kyllinga* management changed fundamentally with the publication of Westbury et al. (2022), which documented the first confirmed case of ALS inhibitor-resistant green kyllinga. The resistant biotype was identified on a golf course in Florida that had a long history of exclusive reliance on ALS-inhibiting herbicides for *Kyllinga* control. Whole-plant dose-response assays demonstrated that the resistance factors were substantially greater than those of susceptible reference populations when treated with halosulfuron and trifloxysulfuron. Molecular characterization identified a target-site mutation in the *als* gene at a conserved amino acid position previously associated with ALS resistance in other weed species, providing mechanistic confirmation that the resistance phenotype arose through target-site modification rather than metabolic or other non-target-site mechanisms. Consistent with this, Yu et al. (2020) demonstrated that target-site resistance is more commonly reported in ALS-resistant sedge populations and typically results in a higher level of resistance than metabolic mechanisms, underscoring the likelihood that affected *Kyllinga* populations will exhibit stable, heritable resistance across progeny.

The confirmation of target-site ALS resistance in *K. brevifolia* is significant for several reasons. First, target-site mutations at conserved positions in the ALS enzyme tend to confer cross-resistance across multiple ALS-inhibiting herbicide classes, meaning that rotation among halosulfuron, trifloxysulfuron, and imaziquin, all ALS inhibitors, is unlikely to provide an effective resistance management solution. Second, the discovery at a single site on a golf course suggests that resistant biotypes may already be present at other intensively managed sites where the selection history has been similar, and that further spread through seed dispersal and equipment movement is a realistic concern. Third, and perhaps most importantly for the purposes of this review, the emergence of ALS resistance necessitates the identification and evaluation of herbicide chemistries with entirely different sites of action for *Kyllinga* management, elevating the importance of research into PPO-inhibiting alternatives such as flumioxazin.

Herbicide Resistance in Turfgrass: Broader Context

Brosnan et al. (2020) provided a comprehensive overview of herbicide-resistant weeds in turfgrass systems, placing the *Kyllinga* resistance problem within the broader context of resistance evolution in managed turf. Their review documented confirmed resistance cases across multiple weed species and herbicide classes in turfgrass, with ALS inhibitors featured prominently among the selection chemistries implicated. The authors highlighted the intensive repeated use patterns characteristic of turfgrass, where the same herbicide or herbicide class may be applied multiple times per season over many consecutive years to the same site, as a primary driver of resistance selection. The high economic value of turfgrass sites, which creates pressure to achieve acceptable weed control with reliable chemistries, often works against the diversification and rotation strategies that are central to resistance management in agronomic crops.

Brosnan et al. (2020) also noted that turfgrass managers have fewer herbicide options compared to many agronomic crops, limiting the practical scope of mode-of-action rotation. The restricted range of turfgrass-safe herbicide chemistries means that resistance in a single weed species to a widely used chemistry can effectively remove a major management tool from the superintendent’s arsenal, making the availability of alternative chemistries with different sites of action particularly valuable. The context reinforces the strategic importance of developing and validating flumioxazin, a PPO inhibitor, as an effective tool for *Kyllinga* management, especially in the context of ALS resistance.

PPO-inhibiting Herbicides: Mechanism, Chemistry, and Turfgrass Use

Protoporphyrinogen oxidase (PPO) inhibitors constitute a structurally diverse class of herbicides that share a common biochemical site of action: the inhibition of PPO, the enzyme that catalyzes the oxidation of protoporphyrinogen IX to protoporphyrin IX in the chlorophyll and heme biosynthetic pathway. Duke et al. (1991) provided the foundational characterization of PPO-inhibiting herbicides, establishing the mechanistic framework that remains central to understanding this herbicide class. Their work demonstrated that PPO inhibition causes the accumulation of protoporphyrinogen IX, which leaks from the chloroplast into the cytoplasm, where it is non-enzymatically oxidized into protoporphyrin IX. This porphyrin accumulates to phytotoxic levels and in the presence of light and oxygen, generates reactive oxygen species (ROS) that rapidly destroy cell membranes and cellular constituents. The result is a characteristic rapid burn-down symptomology of PPO inhibitor exposure: treated plant tissue exhibits water-soaking, bronzing, and necrosis within hours of herbicide application under high light conditions. This rapid activity is a defining characteristic of PPO-inhibitors and distinguishes them from the slower-acting ALS-inhibitors, which typically take days to weeks to produce visible plant death (Dayan et al., 2018). Duke et al. (1991) also documented the broad-spectrum activity of PPO inhibitors across a range of weed species as well as established that species-level differences in sensitivity are related to differences in porphyrin accumulation and detoxification capacity rather than differences in the PPO enzyme itself.

Dayan et al. (2018) subsequently extended this foundational understanding by proving a detailed analysis of the origins, structure, and evolutionary biology of chloroplastic and mitochondrial plant PPO enzymes, with significant implications for understanding both the mechanism of herbicidal activity and the evolution of resistance. PPO enzymes are encoded by two distinct genes in plants: *PPX1* (encoding the plastidic isoform, PPO1) and *PPX2* (encoding both a plastidic and mitochondrial isoform, PPO2), and the relative sensitivity of these isoforms to different PPO-inhibiting herbicides varies among chemical classes (Dayan et al., 2018). Critically, the dual-target nature of PPO inhibition, acting on both chloroplast-targeted and mitochondrial-targeted enzyme isoforms, makes resistance evolution inherently less common than for single-site herbicides such as ALS inhibitors (Dayan et al., 2018). The structural constraints on the PPO active site that confer herbicide binding sensitivity are highly conserved across plant taxa, a feature that underlies the broad-spectrum activity of this herbicide class and simultaneously sets limits on the mutations that can confer resistance without unacceptably impairing catalytic function (Dayan et al., 2018).

Compared with ALS inhibitors, resistance to PPO-inhibiting herbicides has evolved more slowly and in fewer weed species globally, a pattern consistent with the structural constraints on resistance-conferring mutations noted by Dayan et al. (2018). Resistance to oxadiazon has been reported to arise via a target-site mutation in the PPO1 enzyme, and Bi et al. (2020) confirmed that a novel A212T mutation in chloroplastic PPO1 confers resistance to oxadiazon in goosegrass (*Eleusine indica*) collected from turfgrass sites. Notably, because this mutation is specific to the PPO1 isoform, other Group 14 herbicides that primarily target the PPO2 isoform, including flumioxazin, retain the potential to provide control in PPO1-resistant plant populations (Bi et al., 2020). These considerations underscore the importance of using PPO inhibitors, including flumioxazin, as part of a diversified program rather than as exclusive replacements for ALS inhibitors.

Oxadiazon (2-tert-butyl-4-(2,4-dichloro-5-isopropoxyphenyl)- Δ^2-1,3,4-oxadiazolin-5-one) is a PPO-inhibiting herbicide belonging to the oxadiazole chemical class. It has been widely used in turfgrass systems for preemergence and early postemergence control of a range of annual grasses and broadleaf weeds since its introduction in the 1970s . Oxadiazon is particularly valued in turfgrass for its selectivity in warm-season grasses, including bermudagrass (*Cynodon dactylon*) and zoysiagrass (*Zoysia spp*.), as well as its extended residual activity when applied as a granular formulation (U.S. Environmental Protection Agency, 2024). Granular formulations of oxadiazon have been particularly valued in turfgrass management for their safety to the turfgrass stand, especially their minimal effect on root development (Johnson, 1980). Fagerness et al. (2002) confirmed that oxadiazon did not inhibit bermudagrass or zoysiagrass sprig establishment, in contrast to several dinitroaniline herbicides that caused significant reduction in turfgrass cover, establishing oxadiazon's particular utility in vegetative establishment situations where other preemergence options are inadvisable.

Oxadiazon has demonstrated utility specifically for the suppression of annual Cyperaceae species in turfgrass. Belcher et al. (2002) evaluated preemergence applications of oxadiazon against annual sedge and *Kyllinga* species, finding that oxadiazon at labeled rates controlled annual sedge at 94% or greater through seven weeks after treatment in field studies, providing some of the earliest published data on PPO inhibitor activity within the sedge complex in managed turf. This preemergence efficacy against Cyperaceae adds a dimension to oxadiazon's value in turfgrass programs that extends beyond its more commonly cited activity against annual grasses.

Despite its efficacy record, oxadiazon's utility in turfgrass management has been substantially curtailed by regulatory action. In March 2022, the U.S. Environmental Protection

Agency completed its Interim Decision on oxadiazon, reclassifying it as a Restricted Use Pesticide and preventing access by non-certified applicators. The decision further limited applications to 30% of maintained turf acreage within sports fields, golf courses, and sod production facilities, while requiring a 10-foot vegetative buffer from all water sources (EPA Docket No. EPA-HQ-OPP-2014-0782). These restrictions, combined with reported resistance to oxadiazon in goosegrass populations from turfgrass sites (Bi et al., 2020), have created a pressing need for alternative PPO-inhibiting herbicides that can fill the management gap left by oxadiazon's contraction.

Flumioxazin [2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione] is a PPO-inhibiting herbicide of the N-phenylphthalimide chemical class. Like oxadiazon, flumioxazin inhibits PPO and triggers the accumulation of phytotoxic porphyrins and ROS generation cascade as described by Duke et al. (1991); however, the two compounds differ in their precise binding interactions with the PPO enzyme, their physical-chemical properties, and their spectrum of weed activity. It exhibits primarily preemergence activity, controlling annual grasses and broadleaf weeds before or shortly after seedling emergence.

In turfgrass, flumioxazin is registered for use in warm-season grasses, including bermudagrass, zoysiagrass, and centipedegrass, and is applied as a preemergence treatment or early postemergence treatment (Nufarm, 2024). Flessner et al. (2013) conducted the foundational turfgrass evaluation of flumioxazin for annual bluegrass (*Poa annua*) control in bermudagrass, finding that November and December application timings, which coincide with bermudagrass dormancy, provided the best balance of annual bluegrass control, bermudagrass safety, and turfgrass quality. When applied to non-dormant bermudagrass in November, flumioxazin induced rapid necrosis of green tissue and forced early dormancy; despite initial injury, all treated bermudagrass recovered fully by spring green-up with no residual effects on stand quality. This work established the importance of application timing relative to bermudagrass dormancy as the key factor governing safe and effective flumioxazin use in warm-season turfgrass. Flumioxazin's spectrum of activity in turfgrass encompasses many of the same annual weed species controlled by oxadiazon, making it functionally relevant alternative in situations where oxadiazon use has been restricted or discontinued. Research evaluating flumioxazin's performance in turfgrass has generally confirmed adequate preemergence control of target species at labeled use rates, though its residual activity and overall spectrum differ from oxadiazon in ways that may require adjustments in application timing and rate in specific management contexts.

Reed and McCullough (2014) evaluated the tolerance of five warm-season turfgrass species to flumioxazin selectivity across the major warm-season turfgrass taxa. Late-winter applications at rates of 0.21, 0.42, and 0.84 kg ai ha^{-1} caused acceptable injury (less than 20%) to bermudagrass, seashore paspalum (*Paspalum vaginatum*), St. Augustinegrass (*Stenotaphrum secundatum*), and zoysiagrass at three, six, and nine weeks after treatment. Centipedegrass exhibited greater sensitivity, with late-winter applications at the highest rate causing unacceptable injury at six weeks after treatment, though recovery to acceptable levels was achieved by nine weeks in both years of the study. Applications made during active turfgrass growth caused unacceptable injury to all species tested, reinforcing the critical importance of dormancy-dependent application timing established by Flessner et al. (2013).

Recent commercial development of granular formulations of flumioxazin, including Harrell's StayGuard and Nufarm's BroadStar, has expanded the potential application scenarios for this active ingredient in turfgrass. Granular herbicide formulations offer the practical advantage of minimizing foliar contact with the turfgrass canopy, thereby reducing phytotoxicity risk during non-dormant periods and facilitating even distribution across the soil surface. By minimizing foliar contact, enabling soil surface dissolution, and facilitating root absorption, granular flumioxazin formulations may support spring application scenarios for summer weed control that would not be feasible with liquid formulations applied to actively growing turfgrass. Parish (2006) reviewed the characteristics and practical utility of granular applicators for turfgrass, noting that the precision and uniformity of granular application are important determinants of efficacy and safety outcomes, particularly at low application rates.

Flumioxazin for *Kyllinga* Management: Current Evidence and Prospects

The emergence of ALS-resistant *K. brevifolia* as documented by Westbury et al. (2022) creates an urgent need for effective alternative chemistries. Flumioxazin's PPO-inhibiting herbicides have constituted the primary management tools for *Kyllinga* in turfgrass. Cross-resistance between ALS inhibitors and PPO inhibitors is not biochemically plausible, target-site mutations in the ALS enzyme do not affect PPO enzyme sensitivity, and vice versa. Therefore, ALS-resistant *Kyllinga* biotypes remain fully exposed to the phytotoxic mechanism of PPO inhibitors, making flumioxazin a logical candidate for integration into *Kyllinga* management programs in sites where ALS resistance has been confirmed or is suspected.

The precedent of oxadiazon's preemergence activity against Cyperaceae established by Belcher et al. (2002) provides indirect but relevant evidence that PPO inhibitors as a class can suppress members of this weed complex through soil-residual mechanisms. Whether flumioxazin's distinct physical-chemical properties relative to oxadiazon translate to equivalent or superior preemergence suppression of *Kyllinga* germination, or whether its postemergence contract activity against emerged plants contributes meaningfully to population suppression, are questions of considerable practical importance that remain to be directly evaluated.

The biological characteristics of *Kyllinga* species, particularly their heavy reliance on vegetative propagation and their capacity for rapid recolonization, suggest that preemergence control of seedling recruitment combined with postemergence control of established plants will be necessary for effective management. Flumioxazin has demonstrated dual preemergence and postemergence activity in other contexts (Flessner et al., 2013; Reed et al., 2015) and is encouraging in this regard, though direct evaluation against *Kyllinga* is required before firm efficacy conclusions can be drawn. Such studies, which separate the contributions of soil versus foliar uptake to overall herbicide efficacy, are particularly valuable for understanding the mechanistic basis of granular flumioxazin activity and for optimizing application timing relative to weed emergence.

Resistance Management Implications

The documentation of PPO inhibitor resistance in annual bluegrass by Yu et al. (2018) is an important cautionary finding for the design of flumioxazin-based *Kyllinga* management programs. Yu et al. (2018) found that the Georgia annual bluegrass biotype resistant to postemergence flumioxazin remained susceptible to preemergence applications. This biotype's resistance mechanism, involving reduced lipid peroxidation rather than target-site mutation, suggests that the preemergence soil-activity pathway of flumioxazin may not be subject to the same resistance mechanism as the foliar contact pathway, at least in this species. Whether analogous mechanisms could evolve in *Kyllinga* under selection pressure from repeated flumioxazin use is unknown, but the possibility underscores the importance of integrated resistance management even when deploying chemistries that are currently effective against the resistant biotypes of other sites of action.

The value of flumioxazin in *Kyllinga* management extends beyond its utility as an ALS-resistance alternative. As Brosnan et al. (2020) emphasized, the turfgrass weed management context is characterized by a restricted palette of herbicide options, a high-value use environment that demands consistent efficacy, and intensive use patterns that accelerate resistance selection. In this context, any chemistry that provides effective control of problematic weed species while contributing to mode-of-action diversity is valuable on multiple grounds.

Flumioxazin's role as an oxadiazon replacement adds an additional dimension to its potential value in turfgrass programs. Managers who have historically relied on oxadiazon for preemergence weed control, including suppression of annual sedge species and certain *Kyllinga* populations, may find that flumioxazin provides comparable or superior control of target species while also offering activity against the ALS-resistant *Kyllinga* biotypes that threaten the efficacy of their existing programs. The simultaneous resolution of two management challenges, first, the loss of oxadiazon efficacy due to regulatory restrictions and second, the emergence of ALS resistance in *Kyllinga*, positions flumioxazin as a particularly strategically important chemistry for the turfgrass industry.

Tranel and Wright (2002) identified that repeated use of a single site of action as the primary agronomic driver of ALS resistance evolution, and the same principle applies to PPO inhibitors. Any program deploying flumioxazin as an alternative to ALS inhibitors for *Kyllinga* management should incorporate rotation with other available chemistries to slow the potential for PPO resistance selection. The tank-mix compatibility of flumioxazin with multiple herbicide sites of action demonstrated by Reed et al. (2015) provides a practical pathway for integrating flumioxazin into diversified programs rather than using it as a sole-chemistry replacement.

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Chapter 2 Field Evaluation of Granular Flumioxazin For Preemergence Weed Control in Bermudagrass Turf

Abstract

Following 2022 regulatory restrictions on oxadiazon, granular flumioxazin (StayGuard) was evaluated as a replacement preemergence option in bermudagrass turf across two field experiments at Auburn University and Brundidge Country Club in Alabama. Experiment 1 tested flumioxazin alone and sequentially with prodiamine, pendimethalin, or indaziflam across three runs (analyzed separately due to a significant run x treatment interaction). A single spring application controlled cockscomb kyllinga as well as indaziflam and better than prodiamine or pendimethalin alone, while sequential programs with a follow-up May application achieved the highest control (87.5-93.2%), suggesting flumioxazin may have postemergence activity. Flumioxazin also provided smooth crabgrass control, though residual activity declined by 145 DAIA. The StayGuard fertilizer carrier consistently improved bermudagrass color. Experiment 2 evaluated flumioxazin timing and rate for annual bluegrass suppression; results showed it functions as a preemergence complement rather than a standalone tool, with complete control only achieved alongside postemergence partners, and treatment effects undetectable under high *Poa annua* pressure in Run B.

Introduction

Preemergence herbicides are the foundation of weed management in warm-season turfgrass, providing season-long control of annual weeds through the inhibition of seedling germination and early establishment. Herbicides such as prodiamine, pendimethalin, and indaziflam are widely used in preemergence programs on golf courses, athletic fields, and sod production. However, preemergence herbicides provide limited efficacy against established perennial weeds such as cockscomb kyllinga, underscoring the need for complementary tools that can address both emerging annual weeds and established perennial sedge populations within a single program. Additionally, herbicide resistance is a growing concern in turfgrass management, with more than 40 reports of resistant weed species documented in turfgrass systems, particularly on golf courses where the intensity of herbicide inputs is greatest (Brosnan et al., 2020). The rotation of herbicide modes of action and the use of products with multiple or novel sites of action are essential strategies for managing resistance risk.

Oxadiazon has historically served as a primary tool for preemergence sedge and broadleaf weed control in warm-season turfgrass. As a Group 14 protoporphyrinogen oxidase (PPO) inhibitor, oxadiazon is highly effective because it targets both the mitochondrial (PPO2) and chloroplastic (PPO1) PPO isoforms (Dayan et al., 2018). Granular formulations of oxadiazon have been particularly valued in turfgrass management for their safety to the turfgrass stand, especially their minimal effect on root development (Johnson, 1980). However, in March 2022, the U.S. Environmental Protection Agency completed its Interim Decision on oxadiazon, reclassifying it as a Restricted Use Pesticide and imposing significant use limitations, including restricting applications to 30% of maintained turf acreage within golf courses, sports fields, and sod production facilities and requiring a 10-foot vegetative buffer from all water sources (EPA Docket No. EPA-HQ-OPP-2014-0782). These restrictions have substantially curtailed the practical utility of oxadiazon in many turfgrass management programs, creating a need for alternative PPO-inhibiting products.

Flumioxazin is a Group 14 PPO-inhibiting herbicide that has emerged as a logical successor to oxadiazon. Flumioxazin primarily targets the PPO2 enzyme (Zhao et al., 2020) and provides broad spectrum control of grasses, broadleaf weeds, and sedges (Duke, 1991), with characteristically fast-acting activity and long residual soil persistence (Iwashita et al., 2022). Recent commercial development of granular formulations of flumioxazin, including Harrell's StayGuard and Nufarm's BroadStar, has expanded the potential application scenarios for this active ingredient in turfgrass. Granular herbicide formulations offer the practical advantage of minimizing foliar contact with the turfgrass canopy, which can reduce phytotoxicity risk during non-dormant periods and facilitate even distribution across the soil surface. The hypothesis driving the present field research was that granular flumioxazin, applied during spring dormancy break in bermudagrass, could provide effective preemergence control of summer annual weeds across the growing season, either alone or in combination with conventional preemergence herbicides.

The objective of Experiment 1 reported herein was to evaluate the efficacy of granular flumioxazin (StayGuard) applied alone and in sequential combination with prodiamine, pendimethalin, or indaziflam for the preemergence control of cockscomb kyllinga and smooth crabgrass in bermudagrass turf maintained at golf course fairway height, and to assess turfgrass safety and possible phytotoxicity associated with these treatments. The objective of Experiment 2 was to evaluate the efficacy of granular flumioxazin applied at different timings and rates, alone and in combination with postemergence partners, for the suppression of annual bluegrass cover in dormant bermudagrass turf.

Materials and Methods

Experiment 1: Preemergence Weed Control Utilizing Granular Flumioxazin in Bermudagrass Turf

Field research was conducted across three experimental runs at the Auburn University Sports Surface Field Laboratory in Auburn, Alabama. Run A was conducted at the Auburn University Sports Surface Field Laboratory in Auburn, Alabama, during the 2025 growing season. Run B was conducted at the Auburn University Sports Surface Field Laboratory during the 2026 growing season on a different experimental turfgrass stand. Run C was conducted at the Brundidge Country Club in Brundidge, Alabama, during the 2026 growing season. Because weed pressure, weed community composition, and seasonal conditions differed among runs, each run was analyzed independently using a randomized complete block design (RCBD) with four replicates, and runs were not combined for statistical analysis.

Each run was established in bermudagrass (*Cynodon dactylon* [L.] Pers.) maintained at golf course fairway mowing height. Turfgrass was managed according to standard cultural practices for the site throughout the duration of each run, including routine irrigation at the Auburn location and mowing at both sites. Individual plots measured 5 feet by 5 feet at the Auburn locations and 5 feet by 10 feet at the Brundidge location. Twelve treatments were evaluated in each run, arranged in an RCBD with four replications. Treatments included a nontreated control, granular flumioxazin applied alone at a single or sequential timing, three conventional preemergence herbicides applied at a single or sequential timing, and sequential combinations of a conventional preemergence herbicide followed by granular flumioxazin (Table 2-1).

In Run A, Application A was made on March 18, 2025 and Application B on May 15, 2025 (58 days after Application A). In Run B, Application A was made on March 3, 2026 and Application B on April 30, 2026 (58 days after Application A). In Run C at the Brundidge Country Club, Application A was made on March 16, 2026, and Application B on May 11, 2026 (56 days after Application A).

Liquid herbicide treatments were applied using a pressurized CO_2 backpack sprayer calibrated to deliver 280L ha^{-1} (30 gal A^{-1}), through XR Teejet 8002VS flat fan nozzles (Teejet Technologies, Glendale Heights, IA). Granular flumioxazin (StayGuard 22-0-10; Harrell's, Lakeland, FL) was applied at 300 lb A^{-1} (0.42 kg ai ha^{-1}). Granular product for each plot was weighed individually, placed into Whirl-Paks, and distributed evenly across the plot surface by hand. All applications were made under appropriate environmental conditions to minimize the potential for spray drift or granule movement off-target.

Cockscomb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl), and smooth crabgrass (*Digitaria ischaemum* [Schreb.] Schreb. ex Muhl.) percent visual control were evaluated on June 10, July 10, August 10, and September 10, 2025 (84, 114, 125, and 145 DAIA, respectively). In Run B at Auburn in 2026, smooth crabgrass, dichondra (*Dichondra carolinensis* Michx.), and chickweed (*Stellaria media* [L.] Vill.) visual control and bermudagrass color were assessed on June 1, 2026 (84 DAIA). In Run C at Brundidge in 2026, smooth crabgrass and bermudagrass color were assessed on June 8, 2026 (84 DAIA). Visual control ratings were recorded on a scale of 0 to 100, where 0 indicated no visible herbicide effect relative to the nontreated control, and 100 indicated complete weed death. Bermudagrass color was assessed on a 1 to 9 scale, where

1 indicated completely dead turf with no live green tissue visible; 6 indicated acceptable turfgrass color and quality representative of a minimally maintained stand; and 9 indicated optimum dark green color with no visible stress, discoloration, or injury (Beard, 1973). A rating of 6 or greater is generally considered commercially acceptable in turfgrass management contexts.

Data were analyzed using SAS (v9.4; SAS Institute Inc., Cary, NC) with the PROC GLIMMIX procedure. Prior to the individual run analysis, a combined analysis of variance was conducted to determine whether experimental runs could be pooled across environments. For each response variable with data available at comparable evaluation timing across multiple runs, a two-way analysis of variance was performed with treatment, run, and the run-by-treatment interaction as fixed effects, and blocks nested within runs as a random effect. When the run-by-treatment interaction was not significant ($P > 0.05$), data were pooled across runs for a combined analysis and means were presented collectively. When the run-by-treatment interaction was significant ($P \leq 0.05$), indicating that relative treatment performance differed across environments, runs were analyzed independently and means are presented separately by run with discussion of the factors contributing to the differential response. Within each run, treatment effects were evaluated using analysis of variance (ANOVA) with an RCBD model, and treatment means were separated using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$.

Experiment 2: Evaluation of Granular Flumioxazin for Annual Bluegrass (Poa annua) Suppression in Bermudagrass Turf

Two runs of this experiment were conducted at the Auburn University Sports Surface Field Laboratory in Auburn, Alabama, on separate experimental turfgrass stands. Run A was conducted during the 2023-2024 season and Run B during the 2025-2026 season. Because natural annual bluegrass pressure differed substantially between runs, each run was analyzed independently using an RCBD, and runs were not combined for statistical analysis. However, similar trends across each location will be discussed, and a supplementary analysis converting cover to a value relative to the nontreated control was performed to test whether the two runs could be combined despite their differing background pressure.

Six treatments were evaluated in each run (Table 2-2), arranged in an RCBD with four replications (Run A) or three replications (Run B). Treatments consisted of granular fertilizer blends (8-4-16, 12-6-18, or 0-0-10) applied with or without StayGuard flumioxazin (0.125% w/w) incorporated into the carrier, applied alone or in sequential combination with postemergence herbicides (Princep, simazine; Tribute Total, thiencarbazone-methyl + foramsulfuron + halosulfuron-methyl). Application A timings targeted fall preemergence application ahead of the primary annual bluegrass germination window, and Application B timings targeted postemergence activity during active annual bluegrass growth in November. In Run A, Application A was made on September 18, 2023, and Application B on November 17, 2023. In Run B, Application A was made on September 17, 2025, and Application B on November 23, 2025.

The experimental area consisted of bermudagrass turf maintained at golf course fairway mowing height. Annual bluegrass (*Poa annual* L.) percent cover was assessed visually at 56, 84, and 205 DAIA in Run A (November 13, December 11, 2023 and April 10, 2024) and at 84, 114, and 146 DAIA in Run B (December 10, 2025, January 9, and February 10, 2026). Cover was estimated as the percentage of the plot surface occupied by living annual bluegrass on a scale of 0 to 100. Bermudagrass was dormant during all evaluation periods; turfgrass injury ratings were recorded but were uniformly zero throughout both runs and are not reported.

Data were analyzed using SAS (v9.4; SAS Institute Inc., Cary, NC) with PROC GLIMMIX. Prior to individual run analysis, the appropriateness of pooling data across runs was evaluated. The two runs were conducted on separate experimental tiers that differed in natural annual bluegrass pressure: the nontreated control in Run A reached 61.3% cover by the April endpoint (205 DAIA), whereas the nontreated control in Run B had already reached 56.7% cover by December (84 DAIA) and 95.0% by February (146 DAIA). Because of this difference in incoming weed pressure, which fundamentally altered the ability of preemergence programs to express treatment differences, producing significant treatments in Run A but non-significant outcomes in Run B at all evaluation dates, the two runs were not pooled on the raw cover scale, and each is presented independently below. Within each run, treatment effects were evaluated using ANOVA with an RCBD model, and treatment means were separated using Fisher's Protected LSD test at $P \leq 0.05$. Run A and Run B shared a single common evaluation timing, 84 DAIA (December 11 in Run A; December 10 in Run B); at this date only, raw percent cover was converted to a relative cover value (percent of the nontreated control mean within the same run) and analyzed in a combined model including Treatment, Run, and their interaction to evaluate whether the two runs could be combined.

Results and Discussion

Experiment 1: Preemergence Weed Control in Bermudagrass Turf

The three runs of this experiment collectively represent two growing seasons, two experimental tiers at the Auburn University Sports Surface Field Laboratory, and one golf course site. Prior to individual run analysis, a combined two-way ANOVA was conducted on response variables available at comparable evaluation timings across all three runs to determine whether runs could be pooled for a single combined analysis. The run-by-treatment interaction was significant for smooth crabgrass control at the June evaluation (84 DAIA; $P = 0.028$) and for bermudagrass color at the June evaluation ($P = 0.0001$), indicating that relative treatment performance differed across runs at this timepoint. Because these interactions were statistically significant, runs were analyzed independently, and means are presented separately by run for all response variables. The significant interaction for crabgrass control is best interpreted in the context of the ecological and site-level differences among runs rather than as evidence of inconsistent herbicide performance. The primary driver of the interaction was sequential indaziflam (Specticle Flo) which provided 60.0% smooth crabgrass control in Run A but 96.5% and 86.2% in Runs B and C, respectively. This pattern is consistent with the well-documented sensitivity of split-application indaziflam programs to the timing interval and rate of individual applications relative to the weed germination window (Perry et al., 2011). Differences in application timing, seasonal weather conditions, or the developmental stage of germinated crabgrass at the time of Application B may have produced different outcomes across environments for this particular program. All other treatments showed broadly consistent responses across runs, suggesting that the significant interaction was driven primarily by this single treatment rather than by widespread inconsistency across the program set. Additionally, weed species composition at the June 84 DAIA evaluation differed substantially among runs: Run A was dominated by cockscomb kyllinga and smooth crabgrass, Run B saw smooth crabgrass and additionally included dichondra (*Dichondra carolinensis* Michx.) and common chickweed (*Stellaria media* [L.] Vill.), and Run C recorded early emergence coverage of kyllinga and goosegrass (*Eleusine indica* [L.] Gaertn.) in addition to smooth crabgrass control. These differences reflect site-specific weed seed bank composition, seasonal weather patterns, and prior management history at each location rather than experimental inconsistency, and they provide ecologically meaningful information about the breadth of weed management contexts in which granular flumioxazin programs are likely to be deployed. Where response variables were unique to a single run, including cockscomb kyllinga control at all Run A evaluation dates, dichondra and chickweed control in Run B, and goosegrass and *Kyllinga* cover in Run C, runs are presented individually without a pooling test, as cross-run comparison is not applicable for those variables.

Run A: Auburn University Sports Surface Field Laboratory, Auburn, AL, 2025

Weed pressure at the Auburn location during the 2025 growing season was dominated by cockscomb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) and smooth crabgrass (*Digitaria ischaemum* [Schreb.] Schreb. ex Muhl.), with very low natural doveweed (*Murdannia nudiflora* [L.] Brenan) pressure throughout the season. The nontreated control accumulated 64.0% cockscomb kyllinga cover by 145 DAIA, indicating moderate and consistent sedge pressure that was sufficient to clearly discriminate among herbicide programs across the growing season.

Treatment effects on cockscomb kyllinga control were significant at all four evaluation dates ($P < 0.001$, < 0.001, < 0.001, and 0.020 for June 10, July 10, August 10, and September 10, respectively). A single spring application of granular flumioxazin in March provided 91.2% cockscomb kyllinga control at 84 DAIA and maintained 83.5% at 145 DAIA (Table 2-3), a level that was statistically superior to prodiamine (54.2%) and pendimethalin (46.5%) applied alone, neither of which differed significantly from the nontreated control at 145 DAIA (LSD = 32.7). This contrast illustrates a fundamental difference in the spectrum of activity between dinitroaniline herbicides, which are primarily grass preemergence tools with limited sedge activity, and flumioxazin, whose PPO-inhibiting mechanism provides broader activity. The sequential programs pairing a conventional preemergence herbicide with a May follow-up application of granular flumioxazin consistently achieved 87.5 to 93.2% cockscomb kyllinga control, which was statistically superior to their respective single-application counterparts (Table 2-3, Figure 2-1). The contribution of the May flumioxazin application to sedge suppression, even after cockscomb kyllinga had emerged, suggests that granular flumioxazin may possess postemergence activity mediated through root or soil-contact uptake under field conditions, a possibility investigated further in the greenhouse studies reported in Chapter 3. Indaziflam applied as a single application provided 82.5% cockscomb kyllinga control at 145 DAIA, comparable to the single flumioxazin program and consistent with indaziflam’s documented broader spectrum of activity relative to the dinitroanilines.

Treatment effects on smooth crabgrass percent visual control were significant at all four evaluation dates (P < 0.001 for all dates; Table 2-3). Conventional preemergence herbicides, prodiamine, pendimethalin, and indaziflam, controlled smooth crabgrass acceptably (>90%); regardless of application program (95.8 to 98.5% at 145 DAIA; LSD = 15.2), consistent with their established efficacy as grass preemergence standards. Granular flumioxazin applied as a single application controled 91.2% of smooth crabgrass at 84 DAIA but declined to 77.2% by 145 DAIA, significantly lower than the conventional standards, suggesting some limitation in residual activity for grass control over a full season from a single March application. The sequential flumioxazin program (94.2% at 145 DAIA) recovered this gap and performed comparably to the conventional standards. A notable and counterintuitive result was the decline in smooth crabgrass control observed in the sequential indaziflam treatment: indaziflam applied sequentially provided only 66.2% smooth crabgrass control at 145 DAIA, significantly less than the single full-rate application (95.8%). The poor performance in Run A was not replicated in Runs B or C, where this program controlled 96.5 and 86.2% smooth crabgrass at 84 DAIA, respectively, a discrepancy that contributed to the significant run-by-treatment interaction detected in the combined analysis and suggests that the outcome for this program in Run A may reflect site-specific conditions rather than a generalizable limitation of the sequential indaziflam approach.

Bermudagrass color ratings were significantly affected by treatment at the June 10, July 10, and August 10 evaluations (P < 0.001, 0.002, and 0.013, respectively) but not at the final September 10 evaluation (P = 0.331; Table 2-3). At 84 DAIA, sequential programs receiving granular flumioxazin in May, recorded the highest color ratings (8 on a 1-9 scale), significantly greater than the nontreated control (6) and single-application programs. This improvement reflects the nitrogen contribution of the StayGuard 22-0-10 granular carrier; each application at 300 lb A^{-1} delivers approximately 66 lb N A^{-1}, rather than any phytostimulatory effect of flumioxazin, and turfgrass managers using StayGuard should account for this nitrogen input within their seasonal fertility program. By mid-summer, color ratings in some flumioxazin-containing treatments declined modestly, with sequential indaziflam followed by granular flumioxazin recording the lowest color in August 10 (3.8), suggesting potential additive phytotoxicity from that combination during active bermudagrass growth. By September 10, color ratings were statistically uniform across all treatments, confirming complete bermudagrass recovery from any mid-season injury, consistent with Reed and McCullough (2015).

Run B: Auburn University Sports Surface Field Laboratory, Auburn, AL, 2026

The weed community at the Auburn Sports Surface Field Laboratory in 2026 differed substantially from that observed in 2025 during Run A, reflecting year-to-year variation in weed seed bank composition and seasonal weather conditions. Rather than cockscomb kyllinga dominating the nontreated plots, three species were prominent at the June 1, 2026 evaluation (84 DAIA): smooth crabgrass, dichondra (*Dichondra carolinensis* Michx.), and common chickweed (*Stellaria media* [L.] Vill.). The persistence of chickweed, a winter annual that typically germinates in fall and declines with warming temperatures, into early June reflects a cooler-than-average spring. Dichondra, a perennial creeping broadleaf common in southeastern turfgrass systems, had an established presence in the seed bank at this tier, independent of the primary target weed community. Together, these species created an opportunity to assess granular flumioxazin efficacy against a broader weed complex than was targeted in Run A.

Treatment effects on smooth crabgrass at 84 DAIA were highly significant ($P < 0.001$; LSD = 8.7; Table 2-4). Conventional preemergence herbicides, prodiamine (95.0%), pendimethalin (97.0%), and indaziflam (95.8%), provided statistically superior crabgrass control compared to granular flumioxazin applied as either a single (87.0%) or sequential (87.0%) application, consistent with the pattern observed in Run A and with the established strength of dinitroaniline and cellulose biosynthesis-inhibiting herbicides for grass preemergence control. Sequential programs pairing a conventional preemergence herbicide with granular flumioxazin achieved 98.5 to 99.0% crabgrass control, confirming that combining these modes of action delivers reliable broad-spectrum grass management.

Treatment effects on dichondra were significant at 84 DAIA ($P < 0.001$; LSD = 23.5; Table 2-4). All treated programs provided significantly better dichondra control than the nontreated control, though granular flumioxazin applied as a single application (74.5%) was significantly lower than both the conventional preemergence programs and the sequential flumioxazin program (85.0%). This suggests that a single March application of granular flumioxazin may not maintain sufficient residual activity against a perennial broadleaf like dichondra into the early summer evaluation window, while prodiamine (97.0%) and other conventional programs with longer residual profiles performed more consistently. Treatment effects on chickweed were also significant ($P < 0.001$; LSD = 9.8), and granular flumioxazin applied alone (92.5%) performed comparably to the conventional preemergence standards against this winter annual broadleaf, a result consistent with the broad-spectrum preemergence activity that PPO-inhibiting herbicides are known to provide against annual broadleaf species (Duke, 1991). Bermudagrass color ratings reflected the nitrogen fertilizer effect observed in Run A, with sequential programs containing granular flumioxazin producing the highest color at 84 DAIA (P = 0.009; LSD = 1.2; 7.2 to 7.8 on a 1-9 scale).

Run C: Brundidge Country Club, Brundidge, AL, 2026

The weed community at the Brundidge Country Club at 84 DAIA (June 8, 2026) differed from that observed at the Auburn location in either 2025 or 2026, underscoring the site-specific nature of weed pressure in managed bermudagrass turf and the importance of multi-location evaluation. Rather than cockscomb kyllinga dominating the untreated plots, smooth crabgrass (*Digitaria ischaemum*) was the primary weed of concern at this evaluation date, with cockscomb kyllinga (*Kyllinga squamulata*) and goosegrass (*Eleusine indica* [L.] Gaertn.) present at very low levels. The nontreated control accumulated 11.2% goosegrass coverage and 2.5% *Kyllinga* cover at 84 DAIA, reflecting conditions at this golf course where goosegrass has likely been a persistent management challenge given its well-documented tolerance of close mowing heights and heat in warm-season turfgrass systems (Busey, 2003). Smooth crabgrass was not quantified as cover in the nontreated plots because crabgrass control ratings in all plots were relative to the nontreated by definition, but the significant treatment effects for crabgrass control confirm that meaningful crabgrass pressure was present at this evaluation date.

Treatment effects on smooth crabgrass control were highly significant at 84 DAIA ($P < 0.001$; LSD = 15.7; Table 2-5). With the exception of prodiamine applied as a single treatment (71.2%), all herbicide programs provided statistically equivalent and commercially acceptable smooth crabgrass control ranging from 85.0 to 97.5% (LSD = 15.7). The relatively lower performance of single-application prodiamine (71.2%) at Brundidge contrasts with its near-complete crabgrass control in Run A (100.0%) and Run B (95.0%), a difference that may reflect soil texture and/or organic matter differences between the Brundidge golf course fairway and the Auburn research site, as dinitroaniline herbicide activity is known to be sensitive to soil adsorption capacity (Senseman, 2007). Notably, granular flumioxazin applied as either a single (85.0%) or sequential (95.0%) treatment provided statistically competitive crabgrass control at Brundidge, consistent with the pattern observed across all three runs and further supporting its utility as a crabgrass preemergence tool across diverse site conditions. The sequential indaziflam program (86.2%) performed comparably to other programs at Brundidge, in contrast to its anomalously low performance in Run A (60.0%), providing additional evidence that the Run A result for this treatment was site or season-specific rather than a consistent program limitation.

Treatment effects on goosegrass cover were significant at 84 DAIA ($P = 0.008$; LSD = 8.9; Table 2-5. Goosegrass cover in the nontreated averaged 11% but ranged from 0 to 30% across the four replications. Most herbicide programs significantly reduced goosegrass cover relative to the nontreated with flumioxazin single (0%), flumioxazin sequential (0%), pendimethalin single (4%), indaziflam single (1%), prodiamine sequential (1%), pendimethalin sequential (4%), and all three combination programs (0 to 1%) all performing significantly better than the nontreated. The two exceptions were prodiamine single (11%) and indaziflam sequential (15%), neither of which differed significantly from the nontreated. Additional summer evaluations later, when the goosegrass has had time to fully establish are needed to further inform these findings.

Treatment effects on cockscomb kyllinga cover at 84 DAIA were not significant (P = 0.219), and no mean separation was performed. *Kyllinga* pressure was low across the experimental area at this evaluation date, with the nontreated averaging only 2.5% cover, and the absence of statistical discrimination among treatments reflects insufficient weed pressure to express treatment-level differences. This finding is consistent with the general principle that preemergence herbicide evaluations require adequate weed pressure to discriminate among programs, and results from this evaluation date should not be interpreted as evidence that treatments lack activity against *Kyllinga* at this site. Additional summer evaluations that are at a later DAIA, when *Kyllinga* pressure is expected to intensify under warm conditions, will be required to characterize the relative efficacy of these programs.

Bermudagrass color ratings were significantly different among treatments at 84 DAIA (P < 0.001; LSD = 1.2; Table 2-5). Flumioxazin-containing programs produced a striking color response at Brundidge: single and sequential flumioxazin applications and all three combination programs pairing a conventional preemergence herbicide with granular flumioxazin produced the highest color ratings (7.2 to 8.2), all significantly superior to the nontreated control (5.0) and all conventional preemergence herbicide programs without flumioxazin (4.8 to 5.5). This response is consistent with the fertilizer nitrogen contribution of the StayGuard 22-0-10 carrier documented in Run A, and the magnitude of the color difference between flumioxazin-containing and non-flumioxazin programs was notably larger at Brundidge than at Auburn in 2025, possibly reflecting a greater turfgrass nitrogen responsiveness at the golf course site or lower baseline soil nitrogen levels. Turfgrass managers using granular flumioxazin at sites with nitrogen-deficient bermudagrass should be aware of this response and account for the carrier nitrogen contribution within their seasonal fertilizer program to avoid unintended overapplication.

Experiment 2: StayGuard for *Poa annua* Suppression in Bermudagrass Turf

While the warm-season weed management utility of granular flumioxazin represents its primary application in turfgrass, the cool-season annual grass, annual bluegrass (*Poa annua*), poses a distinct and seasonally complementary management challenge in bermudagrass systems. Annual bluegrass is among the most widely distributed and economically significant turfgrass weeds globally, infesting golf courses, athletic fields, and managed turf in virtually every temperate climate zone (Huff, 2003). Its prolific seed production, broad germination window, and tolerance for close mowing make it exceptionally difficult to manage once established, and its bright green color, white seedheads, and bunchy growth habit create visible aesthetic defects in dormant or semi-dormant bermudagrass during the fall and winter months (Gaussoin and Branham, 1989). Preemergence control of annual bluegrass in bermudagrass has historically relied on herbicides applied in late summer to early fall, timed to intercept germinating seeds before establishment. The PPO-inhibiting mode of action of flumioxazin, combined with the availability of granular formulations that can be incorporated into fall fertilizer applications, presents an opportunity to evaluate whether StayGuard can contribute to annual bluegrass suppression programs in addition to its warm-season weed management role.

The two runs of this experiment were conducted under markedly different levels of natural *Poa annua* pressure, which had a decisive effect on the statistical outcomes of each run and altogether illustrated a pattern that is relevant not just to flumioxazin but to preemergence herbicide evaluation broadly: treatment discrimination is only possible when weed pressure is sufficient to challenge the programs under evaluation. In Run A (2023-2024), the nontreated control reached 61.3% *Poa annua* cover by the April 205 DAIA endpoint (Table 2-5), a moderate pressure level that allowed clear treatment separation. In Run B (2025-2026), the nontreated control had already reached 56.7% cover by December, equivalent to the Run A April peak, and the resulting high error variance under intense pressure prevented statistical significance at any evaluation date despite numerically meaningful treatment differences. These two runs, therefore, tell complementary stories: Run A shows what granular flumioxazin can and cannot do against *Poa annua* when conditions allow discrimination; Run B shows what happens when weed pressure is too intense.

Run A and Run B shared a single common evaluation timing, 84 DAIA (December 11 in Run A; December 10 in Run B), allowing a direct comparison once raw percent cover was converted to a relative cover value (percent of the nontreated control mean within the same run). At this shared date, the Treatment x Run interation was not significant (P = 0.78), justifying a combined analysis across both runs. Treatment effects on relative cover were significant ($P < 0.001$; LSD = 24.7), and all five treated programs differed from the nontreated control: September-applied StayGuard alone (43.4% relative cover) and the November-applied StayGuard application alone (74.2% relative cover) bracketed the three sequential programs combining a November StayGuard application with Princep and Tribute Total. No other evaluation date was shared between the two runs at the same DAIA values, so all other timings (56 and 205 DAIA in Run A; 114 and 146 in Run B) remain analyzed independently by run, as reported below.

Run A: Auburn University Sports Surface Field Lab, Auburn, AL, 2023-2024

Treatment effects on *Poa annua* cover were significant at all three evaluation dates (56 DAIA: $P = 0.023$; 84 DAIA: $P = 0.045$; 205 DAIA: $P < 0.001$; Table 2-6). StayGuard 0.125% applied in September, ahead of the primary *Poa annua* germination window, was the only treatment to provide meaningful suppression at 56 DAIA (1.3% cover vs 6.3% in the control; LSD = 3.16; Table 2-6), demonstrating that early preemergence timing is essential for intercepting germinating seedlings before establishment. By December (84 DAIA), the September-only StayGuard application and the control fertilizer followed by StayGuard with postemergence partners maintained the lowest *Poa* cover (7.5% each), while the late granular flumioxazin treatment, which received its StayGuard application in November rather than September, had 15.0% cover, not significantly different from the control (17.5%), confirming that the November timing alone was insufficient to prevent early-fall establishment. By April (205 DAIA), the nontreated control had accumulated 61.3% *Poa annua* cover. The September-only StayGuard application, had reduced cover to 15.0%, which is a meaningful reduction but not a commercially acceptable control. The control blends combined with a November StayGuard application with postemergence partners (Princep and Tribute Total), achieved complete suppression (0.0%). This result demonstrates that granular flumioxazin alone is not a reliable standalone *Poa annua* management tool. Complete season-long suppression required the postemergence companion herbicides, meaning flumioxazin in these programs functioned as a complement rather than the primary active ingredient for *Poa annua* control.

Run B: Auburn University Sports Surface Field Lab, Auburn, AL, 2025-2026

Under the intense *Poa annua* pressure of Run B, treatment effects did not reach statistical significance at any evaluation date (84 DAIA: P = 0.099; 114 DAIA: P = 0.051; 146 DAIA: P = 0.082; Table 2-6). With the nontreated control at 56.7% *Poa* cover by December and 95% by February, the sheer density of annual bluegrass on this tier compressed the differences between treated and nontreated plots and produced error variance too large for the treatment means to be statistically separated with three replications. The control carrier with 300lb StayGuard and postemergence partners treatment, which numerically showed the most suppression at 146 DAIA (61.7% cover versus 95.0% in the control), represents a 33-percentage-point difference that would be commercially significant, but statistical confirmation was not achievable under these conditions. The non-significant outcomes of Run B do not contradict Run A, both runs arrive at the same practical conclusion: granular flumioxazin is not a primary *Poa annua* management tool, and its role within sequential programs is that of a preemergence complement whose contribution depends on prevailing weed pressure and the activity of any postemergence partners applied alongside it. Turfgrass managers at sites with high *Poa annua* seed bank pressure should not expect granular flumioxazin programs to provide commercially adequate suppression, and should rely instead on herbicide programs with well-documented efficacy against this species.

Conclusions

The field studies reported in this chapter collectively demonstrate that granular flumioxazin is an effective preemergence tool for warm-season weed management in bermudagrass turf, particularly for cockscomb kyllinga, while also identifying meaningful limitations in its efficacy as a standalone product for cool-season annual grass management. These conclusions are drawn from data representing two experiments, multiple locations, and multiple growing seasons, and are therefore more broadly applicable than single-location, single-year evaluations.

In Experiment 1, a single spring application of granular flumioxazin at 0.42 kg ai ha^{-1} provided season-long *Kyllinga* suppression at levels comparable to indaziflam and significantly superior to prodiamine or pendimethalin applied alone at the Auburn location in 2025. Sequential programs pairing a conventional preemergence herbicide applied in March with a follow-up granular flumioxazin application in May consistently achieved the highest levels of broad-spectrum weed control and are recommended as the preferred approach where both sedge and grass pressure are anticipated. The observation that granular flumioxazin contributed meaningfully to cockscomb kyllinga suppression even when applied in May, when *Kyllinga* had already emerged, suggests that this formulation possesses postemergence activity against this species under field conditions, a finding supported and further investigated in the complementary greenhouse studies reported in Chapter 3. The mechanism underlying this apparent postemergence activity remains incompletely understood and may involve soil dissolution followed by root uptake, contact activity with emerged tissue during granule application, or volatilization; these possibilities are explored in the controlled-environment studies.

The Auburn Run B location in 2026 revealed a distinctly different weed community compared to Run A, including smooth crabgrass, dichondra, and chickweed at the June 1 evaluation, underscoring that weed pressure and species composition in managed bermudagrass turf vary considerably across sites and seasons, and that herbicide program performance should be evaluated across multiple environments before broad recommendations are made. The observation that granular flumioxazin contributed to cockscomb kyllinga and cool-season broadleaf weed suppression across both locations, while showing consistent limitations for grass control when applied as a single early application, suggests that its optimal role is as a sedge and broadleaf preemergence component within diversified programs.

In Experiment 2, granular flumioxazin did not provide commercially acceptable *Poa annua* control as a standalone product under either the low-pressure conditions of Run A or the high-pressure conditions of Run B. Complete suppression in Run A required postemergence herbicide partners. Under high *Poa* pressure in Run B, treatment effects were not statistically significant, illustrating a fundamental limitation of preemergence programs in high-seed-bank environments. Granular flumioxazin is therefore not recommended as a primary *Poa annua* management tool, and programs targeting annual bluegrass should continue to rely on proven preemergence and postemergence chemistries with documented efficacy against this species.

Across both experiments, the influence of weed pressure on treatment discrimination emerged as a recurring and scientifically important theme. Moderate pressure allows treatment differences to be fully expressed, while very high pressure may overwhelm effective programs before residual activity is established. These dynamics reinforce the value of multi-location, multi-year field research in turfgrass weed science and highlight the difficulty of making universally applicable herbicide recommendations from single-environment evaluations.

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Tables

Table 2-1. Herbicide treatments, trade names, application rates, and application timings codes in Experiment 1 at the Auburn University Sports Surface Field Laboratory, Auburn, AL, and Brundidge Country Club, Brundidge, AL.

Trt.	Herbicide	Trade Name	Rate (ai)	Product Rate	Application Code
1	Nontreated	---	---	---	---
2	Flumioxazin (single)	StayGuard	0.42 kg ai A^{-1}	300 lb A^{-1}	A
3	Flumioxazin (sequential)	StayGuard StayGuard	0.42 kg ai A^{-1} 0.42 kg ai A^{-1}	300 lb A^{-1} 300 lb A^{-1}	A B
4	Prodiamine (single)	Barricade	1.12 kg ai A^{-1}	32 fl oz A^{-1}	A
5	Pendimethalin (single)	Pendulum Aquacap	1.65 kg ai A^{-1}	3.1 pt A^{-1}	A
6	Indaziflam (single)	Specticle Flo	0.049 kg ai A^{-1}	9 fl oz A^{-1}	A
7	Prodiamine (sequential)	Barricade Barricade	0.74 kg ai A^{-1} 0.74 kg ai A^{-1}	21 fl oz A^{-1} 21 fl oz A^{-1}	A B
8	Pendimethalin (sequential)	Pendulum Aquacap Pendulum Aquacap	1.65 kg ai A^{-1} 1.65 kg ai A^{-1}	3.1 pt A^{-1} 3.1 pt A^{-1}	A B
9	Indaziflam (sequential)	Specticle Flo Specticle Flo	0.025 kg ai A^{-1} 0.025 kg ai A^{-1}	4.5 fl oz A^{-1} 4.5 fl oz A^{-1}	A B
10	Prodiamine followed by Flumioxazin	Barricade StayGuard	0.74 kg ai A^{-1} 0.42 kg ai A^{-1}	21 fl oz A^{-1} 300 lb A^{-1}	A B
11	Pendimethalin followed by Flumioxazin	Pendulum Aquacap StayGuard	1.65 kg ai A^{-1} 0.42 kg ai A^{-1}	3.1 pt A^{-1} 300 lb A^{-1}	A B
12	Indaziflam followed by Flumioxazin	Specticle Flo StayGuard	0.025 kg ai A^{-1} 0.42 kg ai A^{-1}	4.5 fl oz A^{-1} 300 lb A^{-1}	A B

Table 2-2. Herbicide treatments, active ingredients, application rates, and application timing codes in Experiment 2 at the Auburn University Sports Surface Field Laboratory, Auburn, AL.

Trt.	Treatment	Active Ingredient	Rate (ai)	Product Rate	Application Code
1	8-4-16 Control Blends	---	---	300 lb A^{-1}	A
2	8-4-16 with StayGuard 0.125%	Flumioxazin	0.42 kg ai A^{-1}	300 lb A^{-1}	A
3	8-4-16 with StayGuard 0.125%	Flumioxazin	0.42 kg ai A^{-1}	300 lb A^{-1}	B
4	8-4-16 Control Blend 0-0-10 with StayGuard 0.125% Princep Tribute Total	--- Flumioxazin Simazine Several*	--- 0.42 kg ai A^{-1} 0.454 kg ai A^{-1} See Note*	300 lb A^{-1} 200 lb A^{-1} 1 qt A^{-1} 1 oz A^{-1}	A B B B
5	8-4-16 Control Blend 0-0-10 with StayGuard 0.125% Princep Tribute Total	--- Flumioxazin Simazine Several*	--- 0.42 kg ai A^{-1} 0.454 kg ai A^{-1} See Note*	300 lb A^{-1} 300 lb A^{-1} 1 qt A^{-1} 1 oz A^{-1}	A B B B
6	8-4-16 Control Blend 0-0-10 with StayGuard 0.125% Princep Tribute Total	--- Flumioxazin Simazine Several*	--- 0.42 kg ai A^{-1} 0.454 kg ai A^{-1} See Note*	200 lb A^{-1} 200 lb A^{-1} 1 qt A^{-1} 1 oz A^{-1}	A B B B

*Tribute Total is made up of Thiencarbazone-methyl (0.00281 kg ai A^{-1}), Foramsulfuron (0.00561 kg ai A^{-1}), and Halosulfuron-methyl (0.00873 kg ai A^{-1}).

Table 2-3. Treatment means for cockscomb kyllinga (*Kyllinga squamulata*) control, smooth crabgrass (*Digitaria ischaemum*) control, and bermudagrass color ratings at 84, 114, 125, and 145 days after initial application (DAIA). Auburn University Sports Surface Field Laboratory, Auburn, AL, 2025.

		84 DAIA (June 10)			114 DAIA (July 10)			125 DAIA (Aug. 10)			145 DAIA (Sept. 10)		
Trt.	Treatment	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)
1	Nontreated	0 c	0 c	6.0 d	0 c	0.0 c	6.0 a	0 c	0 c	6.0 a	0 c	0 c	7.0
2	Flumioxazin (single)	91 a	91 a	7.5 b	93 a	91 a	5.8 a	84 a	88 a	4.5 b	84 a	77 b	6.2
3	Flumioxazin (sequential)	96 a	99 a	8.0 a	96 a	94 a	4.8 c	92 a	94 a	4.2 b	94 a	94 a	6.5
4	Prodiamine (single)	5 c	100 a	6.8 c	33 b	100 a	6.2 a	31 b	96 a	5.8 a	54 b	99 a	6.0
5	Pendimethalin (single)	13 c	100 a	6.8 c	31 b	98 a	6.0 a	36 b	93 a	5.5 a	47 b	96 a	6.0
6	Indaziflam (single)	94 a	96 a	7.0 c	97 a	99 a	6.0 a	92 a	98 a	4.8 b	83 a	96 a	6.8
7	Prodiamine (sequential)	45 b	94 a	7.0 c	61 a	93 a	6.2 a	59 a	92 a	4.8 b	68 a	99 a	7.0
8	Pendimethalin (sequential)	43 b	96 a	7.0 c	46 b	98 a	6.2 a	43 b	98 a	5.2 a	49 b	98 a	6.5
9	Indaziflam (sequential)	94 a	60 b	7.0 c	95 a	69 b	6.0 a	91 a	68 b	5.0 a	91 a	66 b	6.8
10	Prodiamine + Flumioxazin	90 a	100 a	8.0 a	90 a	100 a	5.8 a	86 a	98 a	4.5 b	92 a	96 a	6.8

		84 DAIA (June 10)			114 DAIA (July 10)			125 DAIA (Aug. 10)			145 DAIA (Sept. 10)		
Trt.	Treatment	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)	Cockscomb Kyllinga (control%)	Smooth Crabgrass (control%)	Turf Color (1-9)
11	Pendimethalin + Flumioxazin	91 a	88 a	8.0 a	90 a	95 a	5.5 b	86 a	92 a	4.2 b	88 a	95 a	6.0
12	Indaziflam + Flumioxazin	98 a	91 a	8.0 a	97 a	90 a	5.8 a	90 a	86 a	3.8 b	93 a	68 b	6.8
LSD (P ≤ 0.05)		**27**	**19**	**0.4**	**37**	**16**	**0.6**	**42**	**16**	**1.2**	**33**	**15**	**NS**

z Means within a column and evaluation date followed by the same letter are not significantly different according to Fisher's Protected LSD (P ≤ 0.05). 84 DAIA — Cockscomb kyllinga: P < 0.001; LSD = 27.3. Smooth crabgrass: P < 0.001; LSD = 18.8. Bermudagrass color: P < 0.001; LSD = 0.4. 114 DAIA — Cockscomb kyllinga: P < 0.001; LSD = 37.3. Smooth crabgrass: P < 0.001; LSD = 16.1. Bermudagrass color: P = 0.002; LSD = 0.6. 125 DAIA — Cockscomb kyllinga: P < 0.001; LSD = 41.8. Smooth crabgrass: P < 0.001; LSD = 16.0. Bermudagrass color: P = 0.013; LSD = 1.2. 145 DAIA — Cockscomb kyllinga: P = 0.020; LSD = 32.7. Smooth crabgrass: P < 0.001; LSD = 15.2. Bermudagrass color: P = 0.331; NS (means presented without letter groupings).

Table 2-4. Treatment means for smooth crabgrass (*Digitaria ischaemum*) control, dichondra (*Dichondra carolinensis*), chickweed (*Stellaria media*) and bermudagrass color ratings at 84 days after initial application (DAIA). Auburn University Sports Surface Field Laboratory, Auburn, AL, 2026.

		84 DAIA (June 1)			
Trt.	**Treatment**	**Smooth Crabgrass (Control%)**	**Dichondra (Control%)**	**Chickweed (Control%)**	**Turf Color (1-9)**
1	Nontreated	0 c	0 c	0 c	6.2 b
2	Flumioxazin (single)	87 b	75 b	93 a	5.8 b
3	Flumioxazin (sequential)	87 b	85 a	95 a	6.5 b
4	Prodiamine (single)	95 a	97 a	96 a	5.8 b
5	Pendimethalin (single)	97 a	92 a	98 a	6.5 b
6	Indaziflam (single)	96 a	93 a	98 a	6.5 b
7	Prodiamine (sequential)	97 a	95 a	91 a	5.8 b
8	Pendimethalin (sequential)	98 a	90 a	88 b	6.2 b
9	Indaziflam (sequential)	97 a	92 a	98 a	6.8 a
10	Prodiamine + Flumioxazin	99 a	99 a	96 a	7.8 a
11	Pendimethalin + Flumioxazin	97 a	86 a	95 a	7.8 a
12	Indaziflam + Flumioxazin	99 a	90 a	91 a	7.2 a
LSD (P ≤ 0.05)		**9**	**24**	**10**	**1.2**

z Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$). Crabgrass: $P < 0.001$; Dichondra: $P < 0.001$; Chickweed: $P < 0.001$; Color: $P = 0.009$.

Table 2-5. Treatment means for smooth crabgrass (*Digitaria ischaemum*) control, goosegrass (*Eleusine indica*) cover, cockscomb kyllinga (*Kyllinga squamulata*) cover, and bermudagrass color ratings at 84 days after initial application (DAIA; June 8, 2026). Brundidge Country Club, Brundidge, AL, 2026.

		84 DAIA (June 8)			
Trt.	**Treatment**	**Smooth Crabgrass Control (%)**	**Goosegrass Cover (%)**	***Kyllinga* Cover (%)**	**Color (1-9)**
1	Nontreated	0 c	11 a	3	5.0 b
2	Flumioxazin (single)	85 a	0 b	0	7.2 a
3	Flumioxazin (sequential)	95 a	0 b	0	8.2 a
4	Prodiamine (single)	71 b	11 a	5	5.5 b
5	Pendimethalin (single)	89 a	4 b	3	4.8 b
6	Indaziflam (single)	98 a	1 b	1	5.2 b
7	Prodiamine (sequential)	88 a	1 b	3	5.2 b
8	Pendimethalin (sequential)	90 a	4 b	5	5.0 b
9	Indaziflam (sequential)	86 a	15 a	0	4.8 b
10	Prodiamine + Flumioxazin	93 a	0 b	0	7.8 a
11	Pendimethalin + Flumioxazin	95 a	0 b	1	8.0 a
12	Indaziflam + Flumioxazin	93 a	1 b	0	8.2 a
LSD ($P \leq 0.05$)		**16**	**9**	**NS**	**1.2**

z Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$). Crabgrass control: $P < 0.001$; LSD = 15.7. Goosegrass cover: $P = 0.008$; LSD = 8.9. Kyllinga cover: $P = 0.219$; NS – means presented without letter groupings due to non-significant treatment effect. Color: $P < 0.001$; LSD = 1.2.

Table 2-6. *Poa annua* percent cover by treatment and evaluation date for Experiment 2, Run A (Auburn University Sports Surface Field Laboratory, 2023-2024) and Run B (Auburn University Ó

		Run A: Auburn 2023-2024			**Combined**	**Run B: Auburn 2025-2026**		
Trt.	**Treatment**	**56 DAIA Nov. 13% *Poa* Cover**	**84 DAIA Dec. 11 % *Poa* Cover**	**205 DAIA Apr. 10 % *Poa* Cover**	**84 DAIA % *Poa* Relative to Nontreated**	**84 DAIA Dec. 10 % *Poa* Cover**	**114 DAIA Jan. 9 % *Poa* Cover**	**146 DAIA Feb. 10 % *Poa* Cover**
1	8-4-16 Control Blend	6 ab	18 a	61 a	100 a	57	80	95
2	8-4-16 + StayGuard App A	1 c	8 b	15 b	43 c	28	52	72
3	8-4-16 + StayGuard App B	4 bc	15 a	4 c	74 b	43	65	83
4	Control + StayGuard 200 lb + POST	9 a	14 ab	3 c	71 b	42	60	78
5	Control + StayGuard 300 lb + POST	9 a	14 ab	0 c	71 b	40	57	62
6	StayGuard12-6-18 + StayGuard 200 lb + POST	4 bc	8 b	0 c	45 c	30	50	67
LSD ($P \leq 0.05$)		**3**	**5**	**7**	**25**	**Not Significant P = 0.099, 0.051, 0.082**		

z Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

Chapter 3 Greenhouse Evaluation of Flumioxazin for Control of *Kyllinga* Species and Doveweed

Abstract

Four field-collected *Kyllinga* populations (Missouri, New Jersey, Auburn, and Brundidge) were screened for ALS and PPO inhibitor sensitivity, then evaluated in dose-response and soil-foliar uptake studies. Screening revealed differential ALS inhibitor resistance, ranging from complete cross-resistance in Auburn to a class-specific phenotype in New Jersey not previously documented in *Kyllinga*. Sulfentrazone and flumioxazin controlled all four populations (75-100%) regardless of resistance mechanism. Dose-response assays confirmed this pattern: Auburn produced no fittable curve for trifloxysulfuron (Missouri reference; Brundidge RF = 0.51x, New Jersey RF = 0.2x), but all populations were susceptible to flumioxazin (Auburn reference; Missouri RF = 0.8x, New Jersey RF = 0.63x), confirming no cross-resistance between the two modes of action. A soil-foliar study showed foliar contact, rather than root uptake through soil, drives flumioxazin activity against Kyllinga. Foliar and combined treatments achieved 97-100% control versus 2-24% from granular application, while granular flumioxazin controlled doveweed effectively (73.1%), reflecting its shallower root system.

Introduction

Kyllinga species (Cyperaceae) represent a persistent and increasingly problematic weed complex in warm-season turfgrass systems throughout the southeastern United States. Green kyllinga (*Kyllinga brevifolia* Rottb.), false green kyllinga (*Kyllinga gracillima* Miq.), and cockscomb kyllinga (*Kyllinga squamulata* Thonn. Ex Vahl) are among the most frequently encountered species in managed turfgrass. Their ability to reproduce both vegetatively and by seed enables rapid reinfestation following partial control, and their capacity to thrive in moist, low-mow environments renders them persistent pests within turf (McElroy et al., 2004). Infestations of *Kyllinga* species reduce aesthetic quality, competitive ability, and overall stand uniformity in bermudagrass (*Cynodon dactylon* [L.] Pers.) systems, creating economic and aesthetic concerns for turfgrass managers. Cockscomb kyllinga infests turf through immense seedling establishment (Bunnell et al., 2001). Doveweed (*Murdannia nudiflora* [L.] Brenan), is a weed commonly co-occurring with *Kyllinga* on warm-season turf, where it grows into dense mats that outcompete turfgrass (Atkinson et al., 2019).

Herbicide resistance is a growing issue in turfgrass management. More than 40 reports of resistant weeds have been documented in turfgrass systems, with golf courses bearing a disproportionate burden due to the intensity of weed management inputs (Brosnan et al., 2020). To prevent the development of herbicide resistance, it is essential to rotate products with different modes of action across applications and seasons or to utilize multiple modes of action within a single program. Among the herbicide chemistries historically relied upon for *Kyllinga* control in turfgrass, acetolactate synthase (ALS)-inhibiting herbicides (WSSA Group 2), including the sulfonylurea and triazolopyrimidine chemistries, have been applied extensively. ALS resistance in weeds arises primarily through target-site alterations, though enhanced herbicide metabolism is also possible. Target-site resistance is more commonly reported and typically confers a higher level of resistance (Yu et al., 2020). The repeated selection pressure imposed by ALS-inhibiting herbicides has resulted in documented resistance in multiple *Kyllinga* populations, significantly reducing the efficacy of previously effective management tools and necessitating the identification of alternative modes of action for effective long-term control.

Historically, oxadiazon [2-tert-butyl-4-(2,4-dichloro-5-isopropoxyphenyl)- Δ^2-1,3,4-oxadiazolin-5-one] has served as a foundational preemergence herbicide in warm-season turfgrass management. Oxadiazon is a Group 14 protoporphyrinogen oxidase (PPO) inhibitor that is highly effective because it targets both the mitochondrial (PPO2) and chloroplastic (PPO1) PPO enzymes (Dayan et al., 2018). Granular formulations of oxadiazon have been particularly valued for their turfgrass safety, especially their minimal effect on root development (Johnson, 1980). However, the utility of oxadiazon has been curtailed by regulatory action: in March 2022, the U.S. Environmental Protection Agency completed its Interim Decision on oxadiazon, reclassifying it as a Restricted Use Pesticide and limiting applications to 30% of maintained turf acreage within sports fields, golf courses, and sod production facilities, while requiring a 10-foot vegetative buffer from all water sources (EPA Docket No. EPA-HQ-OPP-2014-0782). Furthermore, resistance to oxadiazon has been reported to arise via a target-site mutation in the PPO1 enzyme, meaning that other Group 14 herbicides have the potential to provide control in resistant plant populations (Bi et al., 2020). These regulatory and resistance developments have created a pressing need for alternative PPO-inhibiting herbicides in turfgrass weed management programs.

Flumioxazin [2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione] has emerged as a logical successor to oxadiazon, as it is also a Group 14 PPO inhibitor, differing from oxadiazon in that it primarily targets the PPO2 enzyme (Zhao et al., 2020). Flumioxazin is more broad-spectrum than oxadiazon, providing control of grasses, broadleaves, and sedges (Duke, 1991), and is characterized by fast-acting activity and long residual control (Iwashita et al., 2022). PPO inhibitors act on two distinct enzyme isoforms, the chloroplast-targeted PPO1 and mitochondrial-targeted PPO2, making resistance evolution inherently less common than for single-site herbicides such as ALS inhibitors. The adoption of PPO-based herbicides within rotation programs can therefore diversify selection pressures, slow resistance evolution, and restore effective sedge management in turfgrass. Additionally, granular formulations of flumioxazin (e.g., Harrell's StayGuard and Nufarm's BroadStar) may further expand its utility by minimizing foliar contact, enabling soil surface dissolution, and facilitating root absorption, thereby supporting application during non-dormant periods without risk of foliar phytotoxicity to the turfgrass stand.

Greenhouse studies are a critical component of herbicide evaluation, enabling the examination of dose-response relationships and formulation effects under controlled conditions that minimize the environmental variability inherent to field experimentation. Field observations from preemergence herbicide trials at the Auburn University Sports Surface Field Laboratory indicated that preemergence herbicides followed by granular flumioxazin achieved effective sedge control, even when those same preemergence treatments applied alone exhibited poor sedge activity. Because cockscomb kyllinga had already emerged prior to the second granular application, these results suggested that granular flumioxazin may possess post-emergence activity through soil or foliar uptake. To investigate this phenomenon under controlled conditions, a greenhouse soil-foliar study was designed to separate the effects of soil versus foliar absorption of flumioxazin across *Kyllinga* species. The objectives of the greenhouse research reported herein were threefold: (1) to conduct an initial screening of field-collected

Kyllinga populations to characterize their response to ALS-inhibiting and PPO-inhibiting herbicides; (2) to quantify the dose-response relationships of *Kyllinga* populations to trifloxysulfuron-sodium (Monument, a triazolopyrimidine ALS inhibitor) and flumioxazin; and (3) to evaluate the efficacy of flumioxazin applied via soil-applied (preemergence), foliar-applied (postemergence), combination, and granular formulation treatments across green kyllinga, false green kyllinga, cockscomb kyllinga, and doveweed (*Murdannia nudiflora* [L.] Brenan).

Materials and Methods

Experiment 1: Initial Population Screening

Four field-collected *Kyllinga* populations of unknown resistance status were obtained for initial herbicide screening. A false-green kyllinga (*K. gracillima*) population from Missouri was submitted by Matt Giese of Syngenta Crop Protection. A second false-green kyllinga population was submitted by Dr. Matthew Elmore of Rutgers University. Two green kyllinga (*K. brevifolia*) populations were collected from warm-season turfgrass sites in Alabama: the Auburn population from the Auburn University Sports Surface Field Laboratory in Auburn, Alabama, and the Brundidge population from the Brundidge Country Club in Brundidge, Alabama. Plants were propagated from stolons to provide a consistent and uniform treatment size and transplanted into 8x8 cm square pots (Dillen Middlefield 4.00 Square Pot; Dillen Products, Middlefield, OH) filled with the surface horizon of a Marvyn sandy loam (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with a pH of 6.5 and 1.1% organic matter. Pots were fertilized weekly at a rate equivalent to 12.2 kg N ha^{-1} using Miracle-Gro water-soluble fertilizer

(ScottsMiracle-Gro, Marysville, OH). Greenhouse conditions were maintained at 32/36°C day/night temperatures, LED lights supplemented natural lighting from October to February to simulate a long-day growing environment, and an automated irrigation system watered plants three times daily to maintain most soil conditions. All plants were approximately three to six tillers in size at the time of application.

Herbicide treatments included trifloxysulfuron (0.28 g ai ha^{-1}; Monument 75WG, Syngenta Crop Protection, Greensboro, NC), flazasulfuron (4.9 g ai ha^{-1}; Katana, SePRO Corporation, Carmel, IN), halosulfuron (93 g ai ha^{-1}; Sedgehammer, Gowan Company, Yuma, AZ), imazosulfuron (92 g ai ha^{-1}; Celero, Valent U.S.A., Walnut Creek, CA), MSMA (4.58 kg ai ha^{-1}), sulfentrazone (0.42 kg ai ha^{-1}; Dismiss, FMC Corporation, Philadelphia, PA), and flumioxazin (0.42 kg ai ha^{-1}; SureGuard, Nufarm, Burr Ridge, IL), along with a nontreated control. A nonionic surfactant (Induce; Helena Agri-Enterprises, Collierville, TN) was included in all spray solutions at 0.25% v/v. Treatments were applied using a pressurized CO_2 system calibrated to deliver 280 L ha^{-1}.

Visual percent control ratings, expressed as a percentage relative to the nontreated control (0 = no injury, 100 = complete plant death), were collected 35 days after the initial application (DAIA). The experiment was arranged as a randomized complete block design (RCBD) with four replications. Statistical analysis was performed using SAS (v9.4; SAS Institute, Cary, NC) with PROC GLIMMIX. Data were subjected to analysis of variance (ANOVA) and means were separated using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$.

Experiment 2: Dose-Response Assays

Dose-response assays were conducted to characterize the sensitivity of the *Kyllinga* populations to both trifloxysulfuron (Monument 75WG) and flumioxazin (SureGuard). Plants were established and maintained under the same greenhouse conditions described in Experiment 1. Treatments consisted of a geometric dilution series spanning 8 doses for each herbicide, plus a nontreated control. For trifloxysulfuron, doses ranged from 0.125x to 16x the labeled rate of 0.53 oz A^{-1} (0.28 g ai ha^{-1}), corresponding to a range of 0.035 to 4.48 g ai ha^{-1}. For flumioxazin, doses ranged from 0.125x to 16x the labeled rate of 12 fl oz A^{-1} (0.42 kg ai ha^{-1}), corresponding to a range of 0.053 to 6.72 kg ai ha^{-1}. All treatments were applied as foliar sprays using the same pressurized CO_2 equipment and surfactant concentration described in Experiment 1.

Visual percent control ratings and above-ground biomass were recorded at 35 days after treatment (DAT). Biomass data were expressed as a percentage reduction relative to the nontreated control mean within each experimental run. This biomass reduction value served as the response variable for all dose-response analyses. Statistical analyses and figure generation were conducted in R version 4.4.2 (R Core Team, 2026) using the *drc* (Ritz et al., 2015), *ggplot2* (Wickham, 2016), and *dplyr* (Wickham et al., 2023) packages.

A four-parameter log-logistic model (LL.4) was fit to the biomass reduction data using the *drm* function in the *drc* package. The four parameters estimated were: *b* (slope at the inflection point of the curve), *c* (lower asymptote), *d* (upper asymptote, representing the maximum biomass reduction achieved at superlethal doses), and *e* (the GR50, defined as the dose producing 50% reduction in shoot biomass relative to the nontreated control). Each population was fit with a separate model rather than combined within a single model object via the *curveid* argument because populations with markedly different curve shapes (e.g. the steep, poorly defined slope obtained for the Brundidge population) caused a joint optimization across all populations to fail to converge; explicit starting parameter values were therefore supplied for each population-level fit. The GR50 for each population was extracted using the *ED* function with the delta method (*interval* = “delta”) to produce 95% confidence intervals. Resistance factors (RF) were calculated as the ratio of the GR50 of each test population to that of the designated susceptible reference population (Missouri for Monument; Auburn for SureGuard). Prior to model fitting, three replicates from the Auburn population SureGuard dose-response assay (Run A, at the 0.125x and 4x doses were excluded after the standardized residuals from a preliminary fit exceeded three standard deviations; each of these replicates showed treated shoot biomass exceeding the nontreated control mean, including one replicate at a superlethal dose (4x the labeled rate) where near-complete control was otherwise observed across all other replicates. Parameter estimates (GR50 and RF) for each population are reported directly on the corresponding dose-response figure.

Populations for which a biologically interpretable dose-response curve could not be fit were excluded from GR50 and RF estimation. The Auburn population was excluded from Monument dose-response curve fitting because biomass reduction showed no dose-dependent response across the entire range evaluated (0.0035 to 0.448 kg ai ha^{-1}), confirming high-level resistance to trifloxysulfuron. The New Jersey population Monument dose-response data technically converged on a model fit but yielded a GR50 of 21,179 kg ai ha^{-1} with an extremely wide confidence interval, indicating a biologically meaningless estimate attributable to a flat biomass reduction response across all doses; initial screening data (90% visual control at the 1x rate) were used as the primary indicator of New Jersey sensitivity to trifloxysulfuron. The Brundidge population was excluded from the SureGuard dose-response curve fitting due to irregular biomass reduction values at sub-labeled doses; this population was classified as susceptible on the basis of visual control at and above the labeled rate.

Dose-response figures were generated using the *ggplot2* package. Smooth predicted curves were generated from the fitted model objects using the predict function across 200 evenly spaced log-scale dose intervals spanning the full range evaluated. Populations for which no curve was fit are represented by observed data points only. The x-axis was scaled logarithmically and expressed as a multiple of each herbicide's labeled field rate (0.125x to 16x) rather than in absolute units; the nontreated control was excluded from the plotted points because a dose of zero is undefined on a log scale, though all nontreated replicates were retained in the underlying biomass reduction calculations and curve fitting. To reduce visual clutter from the full set of individual replicates, observed values are plotted as the mean biomass reduction (± SE) at each tested dose rather than as individual replicate points. A dotted horizontal line indicates the GR50 reference level (50% biomass reduction),and GR50 and resistance-factor estimates for each population are reported in a caption beneath each figure.

Experiment 3: Flumioxazin Soil-Foliar Response Study

A greenhouse study was conducted to evaluate the efficacy of flumioxazin applied via four application methods across three *Kyllinga* species and doveweed. The experiment was arranged as a completely randomized design (CRD) with a 3-by-4-by-5 factorial arrangement and four replications. Target weed species included green kyllinga (*K. brevifolia*), false green kyllinga (*K. gracillima*), cockscomb kyllinga (*K. squamulata*), and doveweed (*M. nudiflora*). Five treatments were evaluated: (1) a nontreated control; (2) soil-applied flumioxazin; (3) foliar-applied flumioxazin; (4) a combination of soil-applied and foliar-applied flumioxazin ; and (5) granular flumioxazin. All flumioxazin treatments were applied at 0.42 kg ai ha^{-1}, with liquid formulations applied as SureGuard (12 fl oz A^{-1}; Nufar3) and the granular treatment applied as StayGuard (300 lb A^{-1}; Harrell's).

Plant material for each species was established under the same greenhouse conditions described in Experiment 1 (36/32°C day/night; LED-supplemented lighting October through February; automated irrigation three times daily). The foliar-applied treatment (POST) was designed to deliver flumioxazin exclusively to aboveground plant tissue while preventing soil contact. To achieve this, the soil surface of each pot was covered with a layer of perlite prior to application. Flumioxazin (SureGuard SC, 12 fl oz A^{-1}; Nufarm was then applied using a pressurized CO_2 boom sprayer calibrated to deliver 280 L ha^{-1} through TeeJet 800VS nozzles. Following application, the perlite was carefully removed from each pot, and plants were subsequently watered by subirrigation to ensure that any active ingredient present on the foliage was not washed into the root zone, thereby isolating foliar uptake as the sole exposure pathway. The soil-applied treatment was designed to deliver flumioxazin exclusively through the root uptake pathway. 10 mL of a flumioxazin solution (SureGuard SC, 12 fl oz A^{-1}) containing 0.0905 mL of flumioxazin per 1 L of water was applied directly to the soil surface of each pot using a syringe, taking care to avoid foliar contact with plant tissue. The combined foliar and soil application treatment was applied as a standard overhead spray using the pressurized CO_2 boom sprayer, allowing flumioxazin to contact both the foliage and the soil surface simultaneously, thereby representing a conventional postemergence spray application scenario. The granular flumioxazin treatment consisted of StayGuard (0.125% W/W granular; Harrell's, Lakeland, FL) applied at 300 lb A^{-1}, equivalent to 0.347 g per pot. Granular product was weighed individually for each pot and distributed evenly across the soil surface by hand. A nontreated control was included for each species.

Visual percent control ratings were assessed at 28 days after the initial application (DAIA) using the 0 to 100 scale described previously. Data were analyzed using ANOVA in SAS (v9.4) with PROC GLIMMIX, and treatment means were separated using Fisher's protected LSD at $P \leq 0.05$. Interactions between species and application method were tested and reported where significant.

Results and Discussion

Experiment 1: Initial Population Screening

Treatment effects on percent visual control were significant for all four *Kyllinga* populations evaluated at 35 days after initial application (DAIA; Missouri: $P < 0.001$; Auburn: $P < 0.001$; Brundidge: $P < 0.001$; New Jersey: $P < 0.001$ (Table 3-1)), indicating that the herbicide treatments differed in efficacy and that population-level responses to the evaluated chemistries were not uniform. The population exhibited four distinct response profiles across the eight treatments evaluated, spanning complete ALS inhibitor resistance to class-specific ALS inhibitor resistance.

The Missouri false green kyllinga (*K. gracillima*) population, which was submitted as a field-collected population of unknown resistance status, demonstrated a pattern of herbicide responses broadly consistent with susceptibility to some, but not all, ALS-inhibiting herbicides. Trifloxysulfuron (Monument, 48.1%) and halosulfuron-methyl (Sedgehammer, 48.1%) provided intermediate control of the Missouri population at 35 DAIA, with values that were statistically greater than the nontreated control but significantly lower than the most effective treatments (LSD = 27.9). Imazosulfuron (Celero, 28.1%) and MSMA (35.0%) provided poor to moderate control that did not differ significantly from the nontreated. In contrast, flazasulfuron (Katana, 86.9%), sulfentrazone (Dismiss, 100%), and flumioxazin (SureGuard, 100%) provided the highest levels of Missouri population control (Table 3-1), with flazasulfuron, sulfentrazone, and flumioxazin all being statistically equivalent and superior to all other treatments. The differential response of the Missouri population to the three triazolopyrimidine and sulfonylurea ALS inhibitors evaluated, with Monument and halosulfurond providing intermediate control while Katana provided nearly complete control, may reflect variation in the breadth of cross-resistance conferred by any target-site mutation present in this population, as specific ALS mutations are known to confer differential levels of resistance across herbicide subclasses (Tranel and Wright, 2002; Yu et al., 2020).

The Auburn green kyllinga (*K. brevifolia*) population exhibited a response pattern consistent with a high level of ALS inhibitor resistance. All four ALS-inhibiting herbicides evaluated, trifloxysulfuron (Monument, 6.9%), flazasulfuron (Katana, 3.8%), halosulfuron-methyl (Sedgehammer, 3.8%), and imazosulfuron (Celero, 8.8%), provided negligible control that was not statistically different from the nontreated control at 35 DAIA (LSD = 14.9). This pattern of complete cross-resistance across all ALS inhibitor subclasses represented in the screening, spanning triazolopyrimidines, sulfonylureas, and imidazolinones, is characteristic of a target-site mutation at a conserved position in the ALS enzyme, such as those at Pro-197, Trp-574, and Asp-376, which are known to confer broad cross-resistance within and across ALS inhibitor chemical classes (Tranel and Wright, 2002). MSMA provided significantly better control of the Auburn population (51.2%) than the ALS inhibitors, consistent with its non-ALS mode of action, though control was incomplete and response was highly variable. Sulfentrazone (Dismiss, 100%) and flumioxazin (SureGuard, 100%) both provided complete control of the Auburn population and were statistically superior to all other treatments, demonstrating that ALS resistance in this population does not confer any cross-resistance to PPO-inhibiting herbicides.

The Brundidge green kyllinga (*K. brevifolia*) population exhibited a pattern intermediate between Missouri and Auburn, with ALS-inhibiting herbicides providing only partial control across the four chemistries evaluated. Monument (14.4%), Katana (31.2%), Sedgehammer (23.1%), and Celero (34.4%) all provided significantly better control than the nontreated but were statistically inferior to MSMA (62.5%), Dismiss (80.6%), and flumioxazin (SureGuard, 75.0%; LSD = 24.0 (Table 3-1; Figure 3-1)). The intermediate ALS inhibitor response in the Brundidge population, combined with higher variability across replications, is consistent with either a lower-level target-site mutation or a metabolic resistance mechanism (Ritz et al., 2015). ALS resistance in turfgrass weeds arising through metabolic mechanisms has been documented in annual sedge (*Cyperus compressus*) by Yu et al. (2020), who found that enhanced herbicide metabolism was associated with incomplete resistance phenotypes like those observed here.

The New Jersey false-green kyllinga (*K. gracillima*) population exhibited a distinct resistance profile from all other populations evaluated. Monument (trifloxysulfuron) provided 90.1% control of the New Jersey population, which was statistically equivalent to MSMA (96.9%), Dismiss (85.1%), and SureGuard (81.4%) (Table 3-1), and was significantly greater than the nontreated control (LSD = 18.3). In contrast, Katana (flazasulfuron, 43.8%), Sedgehammer (halosulfuron-methyl, 36.9%), and Celero (imazosulfuron, 27.5%) provided intermediate to poor control that was statistically inferior to Monument, Dismiss, and SureGuard. This pattern of susceptibility to the triazolopyrimidine ALS inhibitor subclass (Monument) combined with partial to complete resistance to sulfonylurea (Katana, Sedgehammer) and imidazolinone (Celero) subclasses represents a class-specific resistance phenotype not previously documented in *Kyllinga*. This response is consistent with ALS target-site mutation that selectively disrupts the binding of sulfonylurea and imidazolinone inhibitors while preserving susceptibility to triazolopyrimidines, which occupy a distinct binding region within the ALS enzyme (Tranel and Wright, 2002; McCullough et al., 2016). As with all other populations evaluated, sulfentrazone and flumioxazin provided commercially acceptable levels of control of the New Jersey population, further confirming the utility of PPO-inhibiting herbicides for managing ALS-resistant *Kyllinga* regardless of the specific resistance mechanism present.

Experiment 2: Dose-Response Assays

Monument (Trifloxysulfuron) Dose Response

The dose-response assays for trifloxysulfuron confirmed and quantified the differential ALS inhibitor sensitivity observed in the initial screening. Treatment effects on biomass reduction were used to fit a four-parameter log-logistic dose-response curve (Figure 3-1) for populations where a measurable dose-response existed, and GR50, the dose required to achieve 50% reduction in shoot biomass relative to the nontreated control, was derived from the fitted curves. Resistance factors (RF) were calculated as the ratio of each population's GR50 to that of the most susceptible population, identified as Missouri (GR50 = 0.0072 kg ai ha^{-1}).

The Missouri population produced a well-defined dose-response curve across the trifloxysulfuron rate range evaluated (0.0035 to 0.448 kg ai ha^{-1}), with biomass reduction increasing progressively from 23.2% at the lowest dose to 87.5% at the highest dose (Figure 3-1). The fitted curve had an upper asymptote (d) of 85.5%, indicating that even at superlethal doses, or complete control of the Missouri population was not achieved under these conditions, consistent with the presence of some level of tolerance or partial resistance. The slope parameter (b = -1.28) indicated a gradual sigmoidal dose-response relationship typical of populations with incomplete resistance. The GR50 of 0.0072 kg ai ha^{-1} for the Missouri population served as the reference value for resistance factor calculations.

The Brundidge population produced a fittable dose-response curve with a GR50 of 0.0040 kg ai ha^{-1}, yielding a resistance factor of 0.6x relative to Missouri (Figure 3-1). However, the slope parameter (b = -30.43) was unusually steep and the 95% confidence interval on the GR50 estimate was extremely wide (-1,061 to 1,061 kg ai ha^{-1}), reflecting a compressed and irregular dose-response curve in which most of the response was concentrated across a very low dose range. These curve characteristics are inconsistent with a simple target-site resistance mechanism and may reflect heterogeneity within the Brundidge population, including the potential presence of a mixture of resistant and susceptible individuals, which can produce non-sigmoidal or compressed dose-response curves in population-level assays (Ritz et al., 2015). The wide confidence interval indicates that the Brundidge GR50 estimate should be interpreted loosely; the RF of 0.55x is presented as a descriptive value rather than a precise quantification of resistance level.

The Auburn population did not produce a fittable dose-response curve for trifloxysulfuron (Figure 3-1). Biomass reduction ranged from -8.8 to 36.0% across all doses evaluated, with no consistent dose-dependent increase in response, and visual control ratings similarly showed minimal injury across all doses, with no plot exceeding 28% control at any rate. The absence of a dose-response relationship across a 128-fold rate range, from 0.0035 to 0.448 kg ai ha^{-1}, spanning well above field-use rates, is diagnostic of high-level target-site resistance in which the herbicide's site of action has been rendered insensitive to the compound. A GR50 and RF cannot be meaningfully calculated for the Auburn population; instead, the data are presented as evidence confirming complete resistance to trifloxysulfuron. These results are consistent with the first report of ALS inhibitor-resistant *K. brevifolia* by Westbury et al. (2022), who confirmed target-site resistance in a separate population from a Florida golf course. The Auburn population represents an independent confirmation that ALS inhibitor resistance has emerged in *K. brevifolia* at multiple turfgrass sites in the southeastern United States.

The New Jersey population also did not produce a biologically interpretable dose-response curve for trifloxysulfuron (Figure 3-1). A four-parameter log-logistic model technically converged on a fit, yielding a GR50 of 21,179 kg ai ha^{-1} (RF ~ $3x10^6$) with an extremely wide 95% confidence interval. However, examination of the underlying data reveals that biomass reduction was essentially flat across all doses evaluated, ranging from 47.4 to 66.6% at doses from 0.0035 to 0.448 kg ai ha^{-1}, including values at the lowest dose (0.125x, 0.0035 kg ai ha^{-1}) comparable to or greater than those at the highest dose (16x, 0,448 kg ai ha^{-1}). This response pattern is biologically implausible as evidence of resistance, the subthreshold 0.125x dose cannot produce the same biomass suppression as the 16x dose unless some factor other than herbicide activity is responsible for the observed response. The fitted GR50 of 21,179 kg ai ha^{-1} is therefore not interpretable as a meaningful resistance metric. In contrast, the initial screening at the 1x labeled rate demonstrated 90.1% control of the New Jersey population at 35 DAIA, which was statistically equivalent to the most effective treatments evaluated and consistent with susceptibility to trifloxysulfuron. The contradiction between the screening and dose-response results for the New Jersey population likely reflects experimental variability within the dose-response assay rather than a genuine resistance phenotype to trifloxysulfuron, and the initial screening data are considered the more reliable indicator of New Jersey population sensitivity to this herbicide. The biological basis for the high and inconsistent biomass suppression observed at sub-labeled doses in the dose-response assay warrants further investigation.

SureGuard (Flumioxazin) Dose Response

In contrast to the divergent responses observed for trifloxysulfuron, three of the four populations responded robustly to flumioxazin across the dose range evaluated, providing strong evidence that ALS inhibitor resistance in these populations does not confer any cross-resistance to PPO-inhibiting herbicides. Visual control at the labeled rate of 0.42 kg ai ha^{-1} (1x) was 94.6%, 89.1%, 99.8%, and 95.6% for the Brundidge, Auburn, Missouri, and New Jersey populations, respectively, with three of four populations reaching 99.4 to 100.0% control at the 2x rate (0.84 kg ai ha^{-1}) and above (Figure 3-2). These results confirm that flumioxazin provides commercially acceptable levels of *Kyllinga* control across ALS-resistant and partially resistant populations at or above its labeled rate.

The Brundidge population did not produce a fittable four-parameter log-logistic dose-response curve for flumioxazin (Figure 3-2). Biomass reduction values were irregular across the lower portion of the rate range, including a negative value (-39.3%) at the 0.25x dose (0.105 kg ai ha^{-1}), indicating that treated plant biomass at this dose exceeded the nontreated mean, attributable to within-experiment variability. Despite this irregularity at sub-labeled rates, visual control at the 1x rate was 94.6% and reached 100.0% from the 4x rate (1.68 kg ai ha^{-1}) upward, confirming full susceptibility at and above labeled rates. The irregular sub-labeled dose response likely reflects population heterogeneity consistent with the partial ALS resistance phenotype identified in the initial screening, rather than genuine insensitivity to flumioxazin.

One Run A replicates (at the 4x dose) was excluded from the Auburn population dataset prior to fitting after standardization residuals exceeded three standard deviations; showing treated shoot biomass exceeding the nontreated control mean at a superlethal dose where near-complete control was otherwise observed across all other replicates. Two additional replicates at the 0.125x dose were also flagged as candidate outliers but were retained, because excluding them destabilized the fit and produced a fittable dose-response curve with a GR50 of 0.110 kg ai ha^{-1} (95% CI: 0.024-0.196 kg ai ha^{-1}; upper asympotote *d* = 90.5%), which served as the susceptible reference population for flumioxazin resistance factor calculations. The slope parameter (*b* = -1.43) indicated a gradual sigmoidal dose-response typical of a susceptible population with natural variability around the inflection point (Figure 3-2).

The Missouri population produced a GR50 of 0.0696 kg ai ha^{-1} (95% CI: 0.053-0.086 kg ai ha^{-1}; RF = 0.71x), indicating that this population is marginally more sensitive to flumioxazin than the Auburn reference (Figure 3-2). The confidence interval for the Missouri GR50 was well-defined and did not include zero, supporting the reliability of this estimate. The upper asymptote (*d* = 76.2%) was slightly lower than Auburn (*d* = 85.5%), suggesting that maximum biomass suppression at superlethal doses was somewhat lower for Missouri than for the Auburn reference, though both populations were fully controlled at and above the labeled rate.

The New Jersey population produced a technically fitted GR50 of 0.0489 kg ai ha^{-1} (RF = 0.5x relative to Auburn), which would suggest greater sensitivity to flumioxazin than Auburn. However, the standard error on the New Jersey GR50 estimate was 0.157 kg ai ha^{-1}, more than three times the estimate itself, and the 95% confidence interval spanned from -0.287 to 0.384 kg ai ha-1, including negative values that are biologically impossible for a dose. The GR50 parameter for New Jersey was not statistically significant (P = 0.760), further indicating that the fitted curve does not reliably describe the dose-response relationship for this population (Figure 3-2). Examination of the underlying biomass reduction data reveals values ranged from 39.3 to 65.1% across the full rate range, with no consistent dose-dependent increase, suggesting that the fitted curve is driven by variability rather than a true sigmoidal response. Despite the unreliable GR50 estimate, visual control at the 1x rate was 95.6% for the New Jersey population, confirming practical susceptibility to flumioxazin on the basis of visual control performance, and the fitted GR50 is not considered a reliable measure of sensitivity for this population. Repeat assays would be necessary to obtain a reliable GR50 estimate for the New Jersey population.

Across all four populations, flumioxazin provided acceptable control (>89%) at the labeled 1x rate regardless of ALS inhibitor resistance status, and all populations reached complete or near-complete control at the 2x rate. These results confirm that flumioxazin is fully effective against the resistance profiles represented in this study and support its use as an alternative mode of action for managing ALS-resistant *Kyllinga* populations in warm-season turfgrass. The resistance factors for Missouri (RF = 0.63x) and the unreliable New Jersey estimate (RF = 0.44x) both indicate that none of the populations evaluated show reduced sensitivity to flumioxazin relative to the susceptible Auburn reference, providing no evidence of cross-resistance between ALS and PPO inhibitor mechanisms in any population examined.

Experiment 3: Flumioxazin Soil-Foliar Response Study

Treatment effects on percent visual control were significant at all evaluation dates for all four weed species ($P < 0.001$ in all cases; Table 3-2), allowing for full mean separation across treatments and timings. The experiment revealed pronounced differences among application methods in the speed and completeness of *Kyllinga* control, and exposed a striking divergence in the response of *Kyllinga* species versus doveweed (*Murdanna nudiflora*) to the granular flumioxazin formulation. These species-level and application method interactions constitute the primary mechanistic contributions of this study.

Across all three *Kyllinga* species, the foliar-applied and combined foliar and soil-applied treatments achieved the highest and most rapid levels of control at all evaluation dates, consistently reaching 97 to 100% control by 28 DAIA and performing equivalently in all cases (LSD = 18.9, 5.3, and 7.0 for cockscomb kyllinga, false green kyllinga, and green kyllinga, respectively; Table 3-2). This statistical equivalence between foliar-only and combined foliar+soil treatments is mechanistically informative, because the foliar+soil treatment permitted contact with both foliage and soil while the foliar-only treatment isolated foliar exposure via the perlite barrier and subirrigation methodology, the absence of a significant difference between them indicates that foliar uptake alone was sufficient to achieve complete *Kyllinga* control, and that soil contact did not meaningfully augment efficacy beyond what foliar contact provided. These results implicate foliar absorption as the primary and dominant uptake pathway for flumioxazin activity in *Kyllinga* species under these conditions.

The soil-applied treatment, in which flumioxazin was delivered exclusively to the soil surface via syringe to prevent foliar contact, provided intermediate control of cockscomb kyllinga (80.6% at 28 DAIA) and high control of false green and green kyllinga (96.9% and 95.6%, respectively), with both false green and green kyllinga values being statistically equivalent to the foliar and combined treatments (LSD = 5.3 and 7.0). These results indicate that soil uptake of flumioxazin through root absorption is an active and biologically meaningful uptake pathway for *Kyllinga* species, though the rate of control progression was slower for cockscomb kyllinga than for false green kyllinga and green kyllinga. At 7 DAIA, soil-applied flumioxazin provided 31.2% cockscomb kyllinga control compared to 40.0% and 57.5% for the foliar and combined treatments, respectively, with soil-applied being statistically inferior at this early rating date (LSD = 21.2). By 28 DAIA, soil-applied cockscomb kyllinga control had increased to 80.6% but remained significantly lower than foliar and foliar+soil (both 100%), suggesting that root uptake of flumioxazin in cockscomb kyllinga is a slower and ultimately less complete pathway than foliar contact. The greater responsiveness of false green kyllinga and green kyllinga to soil-applied flumioxazin relative to cockscomb kyllinga may reflect species-level differences in root architecture, root surface area, or the kinetics of herbicide uptake and transport within the plant.

The granular flumioxazin treatment was consistently the least effective application method for all three kyllinga species, providing only 24.8%, 3.8%, and 8.8% control of cockscomb kyllinga, false green kyllinga, and green kyllinga at 28 DAIA, respectively. Values that were statistically equivalent for the nontreated control for false green kyllinga and green kyllinga, and significantly lower than all active treatments for all species at all rating dates. The near-complete failure of granular flumioxazin to control *Kyllinga* under greenhouse conditions is a practically important finding. The granular formulation was applied at the same rate of active ingredient as the liquid formulations (0.42 kg ai ha^{-1}), suggesting that the lack of efficacy is attributable to differences in active ingredient availability or delivery rather than to rate. Granular herbicide formulations rely on dissolution of the active ingredient from the granule carrier by soil moisture, followed by movement through the soil profile to the root zone for root uptake. The absence of meaningful *Kyllinga* control from granular flumioxazin, despite clear control from the syringe-applied soil treatment at the same rate, suggests that the granular carrier may have limited the rate or completeness of active ingredient dissolution and root-zone delivery under the greenhouse irrigation regime used in this study. Alternatively, the granular formulation may have released the active ingredient into a zone of the soil profile that was not well-explored by *Kyllinga* roots during the 28-day evaluation window.

Taken together, the *Kyllinga* results support the following mechanistic interpretation. Flumioxazin achieves rapid and complete *Kyllinga* control primarily through foliar contact and absorption, with soil and root uptake providing a meaningful but slower secondary pathway, and granular delivery providing insufficient active ingredient availability to the root zone to achieve acceptable control under these conditions. These findings have direct implications for field application strategies. The observations from the Auburn University Sports Surface Field Laboratory field study, which motivated this greenhouse study, had suggested that sequential applications of granular flumioxazin achieved cockscomb kyllinga suppression even when plants had already emerged at the time of the second application. The present greenhouse data are not fully consistent with a root-uptake explanation for that field observation, given the poor performance of granular flumioxazin in the greenhouse. It is possible that field conditions, including a thicker granule-to-soil contact layer, longer dissolution windows from intermittent rainfall, or greater root system development in established field populations, may provide more favorable conditions for granular flumioxazin dissolution and root-zone delivery than the greenhouse pot environment used here. Field-scale factors such as these may account for the apparent discrepancy between greenhouse and field results and highlight the complementary value of both study types.

The response of doveweed to the five flumioxazin treatments differed markedly from the pattern observed for the *Kyllinga* species, revealing a species-specific divergence in uptake biology that constitutes one of the most compelling findings of the study. The foliar-applied and combined foliar+soil treatments again achieved complete doveweed control by 28 DAIA (both 100%), and the soil-applied treatment reached 78.8% at 28 DAIA, with no significant difference among these three treatments at the final rating date (LSD = 21.4). These results are broadly consistent with the *Kyllinga* findings in confirming that foliar uptake is an effective pathway for flumioxazin activity against doveweed.

In sharp contrast to the near-complete failure of granular flumioxazin against *Kyllinga* the granular treatment achieved 73.1% doveweed control at 28 DAIA, a value statistically equivalent to the soil-applied treatment (78.8%) and significantly greater than the nontreated control (0%), though significantly lower than the foliar and combined treatments (100%). At the earlier 7 and 14 DAIA rating dates, granular flumioxazin was statistically equivalent to the foliar and combined treatments, outperforming the soil-applied syringe treatment at 7 DAIA (37.5% vs 11.9%; LSD = 21.7). This early and robust response to granular flumioxazin in doveweed is substantially more capable of absorbing flumioxazin from a granular carrier via root or soil contact than are *Kyllinga* species, suggesting that doveweed is substantially more capable of absorbing flumioxazin from a granular carrier via root or soil contact than are *Kyllinga* species under the same greenhouse conditions. Several biological characteristics of doveweed may contribute to this differential response. Doveweed is a shallowrooted summer annual broadleaf that develops a fibrous root system concentrated in the uppermost layer of the soil profile, which is also the zone where granule dissolution and initial herbicide release occur. This shallow root distribution may facilitate more efficient contact between germinating root hairs and dissolved flumioxazin than the deeper or more lignified root systems of the perennial *Kyllinga* species. Additionally, doveweed's classification as a broadleaf rather than a sedge may reflect underlying differences in root cell membrane permeability, lipid composition, or transporter protein expression that influence herbicide uptake kinetics.

The differential response of doveweed versus *Kyllinga* to granular flumioxazin provides a biologically meaningful framework for understanding the conditions under which granular PPO-inhibiting herbicides may or may not be expected to provide acceptable weed control in turfgrass. For turfgrass managers, these results suggest that granular flumioxazin formulations applied to actively growing mixed-species weed communities in warm-season turf may achieve useful suppression of doveweed while providing limited activity against established *Kyllinga* populations. Liquid formulations of flumioxazin applied as a foliar spray may be preferred when *Kyllinga* control is the primary objective, while granular formulations may provide a practical and turfgrass-safe alternative for environments where *Kyllinga* has not yet emerged or where doveweed is the primary target.

Conclusions

The greenhouse experiments reported in this chapter provide four distinct and complementary contributions to understanding flumioxazin as a management tool for ALS-resistant *Kyllinga* in warm-season turfgrass. First, the initial population screening confirmed differential levels of ALS inhibitor resistance across four field-collected *Kyllinga* populations and demonstrated that PPO-inhibiting herbicides, specifically sulfentrazone and flumioxazin, remain fully effective regardless of ALS resistance status. This establishes the mechanistic justification for integrating flumioxazin into *Kyllinga* management programs at sites where ALS resistance has been confirmed or is suspected.

Second, the initial screening revealed a class-specific resistance phenotype in the New Jersey false-green kyllinga (*K. gracillima*) population that was not observed in any other population evaluated. The New Jersey population was susceptible to trifloxysulfuron (Monument, 90.1% control) but exhibited partial to complete resistance to the sulfonylurea and imidazolinone ALS inhibitor subclasses represented in the screening. This differential response pattern, not previously documented in *Kyllinga*, is consistent with a target-site mutation that selectively disrupts herbicide binding within specific ALS inhibitor subclasses while preserving susceptibility to others. The discovery of this class-specific resistance profile underscores the diversity of resistance mechanisms that can coexist across *Kyllinga* populations and highlights the importance of multi-herbicide screening when characterizing resistance in field-collected populations.

Third, the dose-response assays quantified the degree of ALS resistance in each population and confirmed the absence of cross-resistance to flumioxazin across the resistance spectrum evaluated. The Auburn population's failure to produce a dose-response curve to trifloxysulfuron across a 128-fold rate range is diagnostic of high-level target-site resistance and represents an independent confirmation that ALS-resistance has emerged in *K. brevifolia* at multiple turfgrass sites in the southeastern United States, consistent with the first report by Westbury et al. (2022). The resistance factor of 0.56x calculated for the Brundidge population relative to Missouri indicates that this population is not more resistant than the Missouri reference and may reflect a mixed population with heterogeneous sensitivity rather than a fixed target-site mutation. All four populations were fully susceptible to flumioxazin at and above the labeled rate, confirming that flumioxazin is an effective tool across the full range of ALS resistance profiles represented in this study. The New Jersey population GR50 estimate for flumioxazin was not statistically reliable (P = 0.760; 95% CI including negative values), and this population is classified as susceptible to flumioxazin on the basis of 95.6% visual control at the labeled rate.

Fourth, the soil-foliar response study revealed that flumioxazin's activity against *Kyllinga* species is driven primarily by foliar contact and absorption, with granular delivery providing insufficient active ingredient availability to the *Kyllinga* root zone to achieve acceptable control under greenhouse conditions. This finding has important implications for interpreting the field results presented in Chapter 2, where granular flumioxazin applied in May provided meaningful cockscomb kyllinga suppression despite plant emergence prior to the second application. The discrepancy between greenhouse and field results for granular flumioxazin against *Kyllinga* may reflect differences in root system development, granule-to-soil contact surface area, dissolution dynamics under field rainfall patterns, or the potential for some foliar contact during broadcast granule application. Further research under field conditions with specific attention to the timing of *Kyllinga* emergence relative to granule application is warranted to resolve this question.

The divergent response of doveweed to granular flumioxazin, where this species showed substantially greater responsiveness to soil-delivered active ingredient than *Kyllinga* species, provides a biologically meaningful framework for formulation selection in mixed-species weed communities. Granular flumioxazin may be most appropriately used as a preemergence tool applied before *Kyllinga* emergence, as a doveweed management tool, or in combination with an additional active ingredient to maximize efficacy across the weed complex. Taken together, these findings support flumioxazin as an effective and versatile tool for managing ALS-resistant *Kyllinga* in warm-season turfgrass and identify foliar uptake as the primary pathway underlying flumioxazin activity against sedge species in this system.

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Tables

Table 3-1. Initial *Kyllinga* population screening: percent visual control at 35 DAIA for four field-collected populations. Combined across two experimental runs. Auburn University Pesticide Research Greenhouse, 2025-2026.

Trt.	**Herbicide**	**Brundidge (*K. brevifolia*) % Control**	**Auburn (*K. brevifolia*) % Control**	**Missouri (*K. gracillima*) % Control**	**New Jersey (*K. gracillima*) % Control**
1	Nontreated	0 c	0 c	0 c	0 c
2	Trifloxysulfuron	14 b	7 c	48 b	90 a
3	Flazasulfuron	31 b	4 c	87 a	44 b
4	Halosulfuron	23 b	4 c	48 b	37 b
5	Imazosulfuron	34 b	9 c	28 b	28 b
6	MSMA	63 a	51 b	35 b	97 a
7	Sulfentrazone	81 a	100 a	100 a	85 a
8	Flumioxazin	75 a	100 a	100 a	81 a
---	LSD ($P \leq 0.05$)	24	15	28	18

z Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$). Brundidge $P < 0.001$. Auburn $P < 0.001$. Missouri $P < 0.001$. New Jersey $P < 0.001$.

Table 3-2. Flumioxazin application method treatment means for percent visual control of all species across all evaluation dates.

Cockscomb Kyllinga (*K. squamulata*) Control (%)

Trt.	Treatment	7 DAIA	14 DAIA	21 DAIA	28 DAIA
1	Nontreated	0 d	0 c	0 c	0 d
2	Granular Flumioxazin	5 c	8 c	12 c	24 c
3	Foliar + Soil	58 a	95 a	100 a	100 a
4	Soil Applied	31 b	67 b	77 b	81 b
5	Foliar Applied	40 a	88 a	99 a	100 a
---	LSD ($P \leq 0.05$)	21	14	18	19

False Green Kyllinga (*K. gracillima*) Control (%)

Trt.	Treatment	7 DAIA	14 DAIA	21 DAIA	28 DAIA
1	Nontreated	0 b	0 b	0 b	0 b
2	Granular Flumioxazin	0 b	4 b	4 b	4 b
3	Foliar + Soil	57 a	93 a	97 a	98 a
4	Soil Applied	51 a	85 a	92 a	97 a
5	Foliar Applied	58 a	89 a	97 a	99 a
---	LSD ($P \leq 0.05$)	13	10	8	5

Green Kyllinga (*K. brevifolia*) Control (%)

Trt.	Treatment	7 DAIA	14 DAIA	21 DAIA	28 DAIA
1	Nontreated	0 c	0 b	0 b	0 c
2	Granular Flumioxazin	1 c	11 b	9 b	9 b
3	Foliar + Soil	64 a	95 a	100 a	100 a
4	Soil Applied	39 b	83 a	91 a	96 a
5	Foliar Applied	48 a	89 a	99 a	100 a
---	LSD ($P \leq 0.05$)	20	15	9	7

Doveweed (*M. nudiflora*) Control (%)

Trt.	Treatment	7 DAIA	14 DAIA	21 DAIA	28 DAIA

1	Nontreated	0 b	0 b	0 c	0 c
2	Granular Flumioxazin	38 a	53 a	62 b	73 b
3	Foliar + Soil	52 a	79 a	91 a	100 a
4	Soil Applied	12 b	21 b	53 b	79 a
5	Foliar Applied	43 a	69 a	92 a	100 a
---	LSD ($P \leq 0.05$)	22	28	30	21

z Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$). All treatments F-tests significant at $P < 0.001$.

Figures

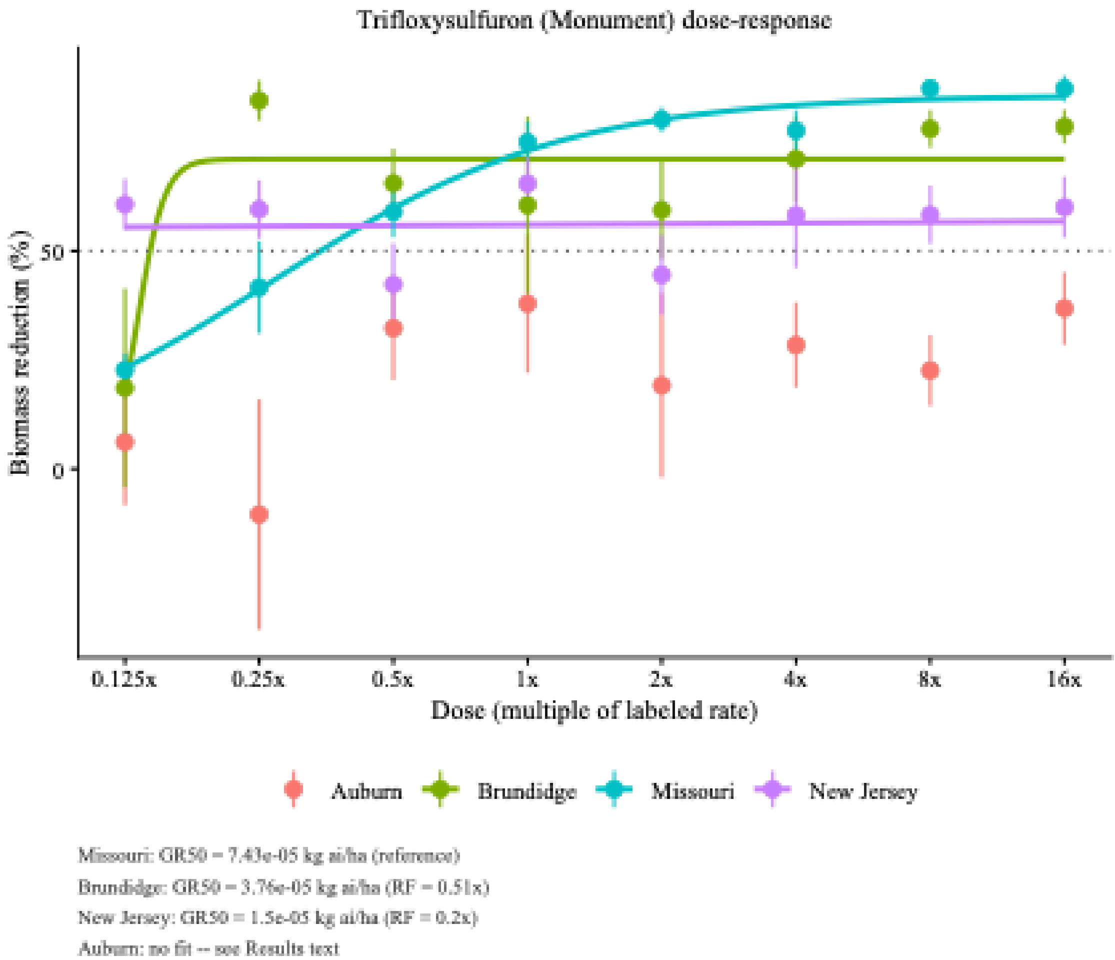

Figure 3-1. Dose-response curves for trifloxysulfuron (Monument) applied to four *Kyllinga* populations. Missouri served as the susceptible reference (GR50 = 0.0743 g ai ha^{-1}); Auburn showed no dose response, confirming resistance. Auburn University Pesticide Research Greenhouse, 2025-2026.

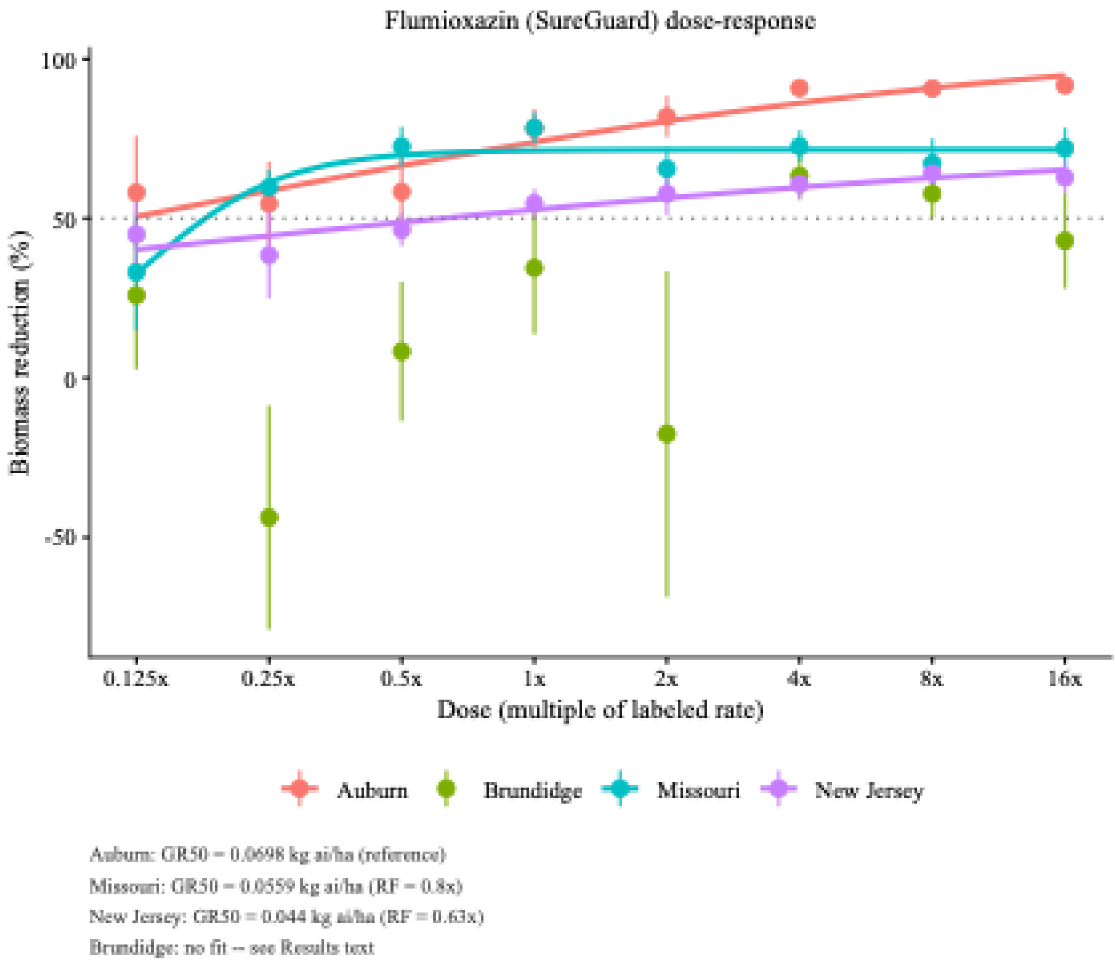

Figure 3-2. Dose-response curves for flumioxazin (SureGuard) applied to four *Kyllinga* populations. Auburn served as the susceptible reference (GR50 = 0.0698 kg ai ha^{-1}); no curve was fit for Brundidge. Auburn University Pesticide Research Greenhouse, 2025-2026.