Assessing Drift and Lateral Mobility of Flazasulfuron and Trifloxysulfuron Sodium

by

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ABSTRACT

. Flazasulfuron is one of the newest sulfonylurea (SU) herbicides to be registered for use in the fine turf industry. Flazasulfuron is safe for use on bermudagrass (*Cynodon dactylon)*, and zoysiagrass (*Zoysia japonica*) yet controls several grass, broadleaf, and sedge weeds. In fine turf, flazasulfuron controls cool-season grasses such as tall fescue (*Festuca arundinacea*) and perennial ryegrass (*Lolium perenne*) without harming warm-season grasses. Although SU herbicides like flazasulfuron bring several potential benefits to turfgrass markets, there are also several concerns related to using these herbicides in turfgrass areas. For many plant species, SU herbicides can cause phytotoxicity or death at less than 1 g ai/ha^{-1}indicating small quantities of active ingredient are required to cause problems if herbicide moves in the environment. Herbicide moves to nontarget plants either after it has been applied via lateral relocation or during application via spray drift. Trials were conducted to evaluate flazasulfuron and trifloxysulfuron sodium tracking, runoff and drift in turfgrass environments. Field trials were conducted at six locations across the US to evaluate effects of irrigation, herbicide treatment, nontreated buffer distance, and time of tracking on creeping bentgrass (*Agrostis stolonifera*) putting green response to dislodged herbicide residues. Although average turf injury did not exceed 2%, significant differences were noted when treated plots were irrigated prior to tracking. In addition, putting green injury was negatively correlated and normalized difference vegetative index was positively correlated with increasing buffer distance. Data indicate the importance of post treatment irrigation to reduce lateral relocation of SU herbicides like flazasulfuron and trifloxysulfuron sodium in turfgrass. In other studies, herbicides were applied to turfgrass on 7 to 11 % slopes and perennial ryegrass injury was assessed at various distances down slope following an irrigation or rainfall event. Herbicide movement in runoff water was indicated by perennial ryegrass discoloration as much as 18 m below treated plots when excessive herbicide rates were applied to saturated soils. Based on perennial ryegrass injury, flazasulfuron at the rates tested was equivalent or more mobile than trifloxysulfuron sodium and equivalent or less mobile than pronamide when subjected to irrigation or rainfall soon after application to saturated soils. To assess spray drift, a bioassay based on corn height reduction was conducted and corn plants were exposed to potential spray drift in field conditions using conventional turfgrass spray equipment. A sprayer was operated when wind speeds were between 6.4 and 9.6 km h^{-1} and sentry plants were placed various distances between 0 and 30 m down wind. Wind speeds and direction were confirmed with anemometers and neutrally-buoyant balloons. Herbicide drift was not detected beyond 4.6 m downwind of either herbicide application. Data suggest a 5- to 8-m nontreated buffer area should sufficiently protect neighboring cool-season

turfgrasses and other plants against flazasulfuron drift, runoff, and tracking as long as product is not applied to saturated soils and irrigated prior to traffic.

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Table of Contents

List of Tables

Chapter 1. Literature Review

Chapter 2. Creeping Bentgrass Putting Green Response to Flazasulfuron and Trifloxysulfuron Sodium Deposited via Foot Traffic

Chapter 3. Perennial Rye Response to Flazasulfuron and Trifloxysulfuron Sodium Deposited by Runoff Water

Chapter 4. Field Assessment of Flazasulfuron and Trifloxysulfuron Sodium Drift Using a Corn (*Zea Mays*) Bioassay

List of Figures

Chapter 4. Field Assessment of Flazasulfuron and Trifloxysulfuron Sodium Drift Using a Corn (Zea mays) Bioassay

Chapter 1: Literature Review

Flazasulfuron, marketed under the names Chikara™, Katana™, Mission™, Parandol™ and Shibagen™ is registered in several countries including Japan, Brazil, Spain, South Korea, France, Mexico, Columbia, and South Africa for weed control in crops such as grapes (*Vinus* spp.), olives (*Olea europaea* L.), and sugar cane (*Saccharum officinarum* L.) as well as fine turf (Anonymous 2009a; Durigan-Marcel et al. 2005; Senseman 2007; Yoshii 2003). Flazasulfuron belongs to the sulfonylurea herbicide class of chemistry which contains over 20 unique compounds. Sulfonylurea herbicides inhibit acetolactate synthase [EC 4.1.3.18] (ALS), an initial enzyme in the biosynthetic pathway for production of branched chain amino acids leucine, isoleucine and valine (Bernasconi et al. 1995; Smith et al. 1989). Once branched chain amino acid production is interrupted, cell division stops while precursor compounds build up to toxic levels within the plant. Phytotoxic symptoms include red and purple discoloration on older leaves and chlorosis at the growth points followed by stunting prior to death (Senseman, 2007). Desirable characteristics of SU chemistry include low use rates, low mammalian toxicity and high crop selectivity (Bernasconi et al. 1995). In 1982 DuPont launched the first SU, chlorsulfuron, marketed as Glean™ for use in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). Sulfonylurea herbicide popularity increased with the introduction of nicosulfuron in 1989 which was developed by Ishihara Sangyo Kaisha Corporation (ISK) and sold to DuPont for use in US agronomic crops. Marketed as Accent™, nicosulfuron was unique due to postemergence control of Johnsongrass [*Sorghum halepense* (L.) Pers.] and other grass species in corn (*Zea mays* L.) (Fahl et al. 1997; Nagabhushana et al. 1995).

Flazasulfuron, like other sulfonylurea herbicides, controls important agronomic weeds including yellow nutsedge (*Cyperus esculentus* L.), purple nutsedge (*C. rotundus* L.), smooth crabgrass spp. [*Digitaria ischaemum* (Schreb. ex Schweig.) Schreb.], green foxtail [*Setaria viridis* (L.) P. Beauv], annual bluegrass (*Poa annua* L.), goosegrass [*Eleusine indica* (L.) Gaertn.], shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], chickweed spp. [*Cerastium* spp. L., *Stellaria media* (L.) Vill.], and dock (*Rumex* spp. L.) (Anonymous 2009; Brecke et al. 2008; Hutto et al. 2008b; Willis et al. 2007). Flazasulfuron is safe for use in bermudagrass [*Cynodon dactylon* (L.) Pers.] and zoysiagrass (*Zoysia japonica* Steud.) and was conditionally registered in the United States for use on these turfgrasses in 2007 (Tompkins 2007). Flazasulfuron is similar in herbicidal activity and turfgrass safety to foramsulfuron, rimsulfuron, and trifloxysulfuron sodium, which were all labeled in US turfgrass since 2001 (Senseman 2007). These herbicides are commonly used to transition overseeded bermudagrass back to a monoculture by controlling fall seeded perennial ryegrass (*Lolium perenne* L.) the following spring (Harrell et al. 2005; Rolfe et al. 2007). Bermudagrass is often over seeded with perennial ryegrass in cool climates to increase aesthetics in the winter months and requires ryegrass control in the spring for optimal bermudagrass development (Beard 1973; Yelverton 2005). In fine turf, spring applications of flazasulfuron control perennial ryegrass in bermudagrass fairways and athletic fields faster and more effectively than other products currently available. (Rolfe et al. 2007). Flazasulfuron also controls other cool-season grasses like tall fescue (*Festuca arundinacea* Schreb.), annual bluegrass, and creeping bentgrass (*Agrostis stolonifera* L.) (Boyd 2005; Brecke 2005; Toler 2007). Flazasulfuron and trifloxysulfuron sodium are among the most effective sedge control herbicides available to turfgrass managers.

Flazasulfuron at 60 g ai/ha reduced purple nutsedge tuber production 86% while glyphosate at 1500 g ai/ha reduced tuber production 69% (Freitas et al. 1997). Southern crabgrass [*Digitaria ciliaris* (Retz.) Kloeler] control with flazasulfuron was equivalent to monosodium methanearsenic acid (MSMA) (Brecke et al. 2008). In addition to cool-season grasses and sedges, flazasulfuron also controls some species of broadleaf weeds that are otherwise difficult to control with currently-available herbicides. Virginia buttonweed (*Diodia virginiana* L.) was controlled 93% at 10 weeks after treatment with three sequential applications of flazasulfuron at 50 and 80g ai/ha and was equivalent to industry standards (Hutto et al. 2008a).

Although SU herbicides like flazasulfuron bring several potential benefits to turfgrass markets, there are also several concerns related to using these herbicides in turfgrass areas. For many plant species, SU herbicides can cause phytotoxicity or death at less than 1 g ai/ha^{1-} (Senseman 2007) indicating small quantities of active ingredient are required to cause problems if herbicide moves in the environment. Herbicides may injure nontarget plants by lateral relocation after the product is applied to the target or by missing the target altogether. The three primary ways herbicide may move to nontarget areas and injure sensitive plants include tracking, runoff, and spray drift.

Lateral relocation is defined as the movement of herbicide from a treated area onto unintended areas. Methods of lateral relocation include tracking and runoff. Tracking occurs when herbicide is dislodged from treated surfaces, moved to adjacent turfgrass, and deposited when equipment tires or foot traffic traverse both areas (Barker et al. 2006; Bowhey et al. year; Willis and Askew 2008). Runoff occurs when soil is infiltrated to full capacity and excess water from irrigation or rainfall flows over land (Muller et al. 2006; Scherrer and Naef 2003). Runoff can also occur when water is introduced faster than the soil infiltration rate (Muller et al. 2006; Scherrer and Naef 2003). As water flows over land, it can dislodge herbicide from treated surfaces and carry it to be deposited elsewhere along the watershed (Gouy et al. 1999). Both tracking and runoff have the possibility of causing injury to susceptible species. The potential for relocating sulfonylurea herbicides, including flazasulfuron, onto sensitive turfgrass is a concern for turfgrass managers. Absorption and translocation of SU herbicides varies by crop and weed species (Koger et al. 2005; Martini and Durigan 2004; McElroy et al. 2004). Total absorption of ^{14}C-halosulfuron after 96 hours was 65% in kyllinga (*Kyllinga brevifolia* Rottb.) and false-green kyllinga (*Kyllinga gracillima* Miq.) (McElroy and Yelverton 2004). Trifloxysulfuron sodium absorption into leaf tissue was 43% for tobacco (*Nicotiana tabacum* L.), 65% for palmer amaranth (*Amaranthus palmeri* S. Watson.) and Texasweed [*Caperonia palustris* (L.) A. St.-Hil.], 47% for green kyllinga and false-green kyllinga, 53% for Jimsonweed (*Datura stramonium* L.), 26% for cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.), and 42% for sicklepod (*Senna obtusifolia* (L.) Irwin & Barneby.) (Askew and Wilcut 2002; Matocha et al. 2006a; McElroy and Yelverton 2004; Troxler et al. 2007). Since approximately half of sulfonylurea herbicide is absorbed by plant foliage, the remaining unabsorbed herbicide could potentially be relocated to nontarget areas.

Tracking

Previous work with flazasulfuron, foramsulfuron, metsulfuron, rimsulfuron, and trifloxysulfuron sodium has indicated potential for all of these herbicides to move via tracking (Barker et al. 2005, 2006; Willis and Askew 2008). Superintendents have reported relocation of sulfonylurea herbicides from bermudagrass onto creeping bentgrass causing unacceptable injury

(W.B Gallager and M. Vaughn, personal communication). Most problems on golf courses occurred when equipment used to mow creeping bentgrass traversed treated areas and returned to the creeping bentgrass or excessive rainfall occurred soon after treatment and runoff injured sensitive grasses down slope of the treated area (Askew and Murphy 2009; Barker et al. 2005, 2006; Willis and Askew 2008). Barker et al. (2005, 2006) described creeping bentgrass injury from rimsulfuron lateral relocation and elucidated irrigation regimes to wash nonabsorbed herbicide from treated leaves to mitigate the problem. Flazasulfuron was tracked more by mower tires when dew was present and high herbicide rates were applied than when leaves were dry and low rates were applied (Willis and Askew 2008). In the same study, the authors conclude that the distance of observable creeping bentgrass injury increased 0.6 m with each 10 g ai ha^{-1} increase in flazasulfuron rate. In these studies that evaluated tracking of SU herbicides, data suggest bentgrass injury can be minimized by irrigating the treated area after application, using low rates near sensitive turf, and maintaining a buffer of 1.5 to 4.5 m nontreated turf between the treated area and sensitive grasses (Barker et al. 2005, 2006; Willis and Askew 2008). In a nonreplicated study from Japan, foot traffic injured creeping bentgrass after traversing treated zoysiagrass and a 25-m nontreated buffer area (ISK Bioscience, unpublished data). Based on this study, a 30-m nontreated buffer zone was specified as a requirement in the US EPA label submission for flazasulfuron. Previous work that evaluated mower traffic following treatment indicates a 5-m buffer is sufficient to prevent injury to adjacent turf (Barker et al. 2005, 2006; Willis and Askew 2008). The contribution of foot traffic to flazasulfuron lateral relocation has not been assessed in the US. In the work contained herein, our first objective was to evaluate the effects of buffer distance, post-treatment irrigation, and herbicide treatment on creeping bentgrass putting green injury from foot traffic that traversed treated areas and the adjacent putting green.

Runoff

Herbicide sorption and desorption are processes impacting herbicide efficacy, dissipation, and mobility in soil (Harper 1994). Sorption refers to herbicide removal from the soil solution by adsorption, absorption or dissipation and desorption is the reverse process releasing bound molecules back into soil solution (Gouy et al. 1999; Harper 1994). Adsorption is the affinity or "binding" of molecules to soil particles or water. Absorption refers to penetration of molecules into plants, microorganisms, or other areas. Dissipation is loss of herbicide molecules through various degrading mechanisms. Adsorption has a direct effect on herbicide mobility in runoff water as it relates to the herbicide's affinity for water compared to that of soil particles (Harper 1994; Martini and Durigan 2004; Shuman et al. 2000). Absorption and dissipation, in time, can reduce the total amount of herbicide available for movement (Harper 1994; Martini and Durigan 2004; Sarmah and Sabadie 2002). Herbicide chemical characteristics influencing sorption are: water solubility, acid dissociation constant (pK_a), ionic charge, transformation kinetics and vapor pressure (Capel et al. 2001; Harper 1994). Herbicide solubility acid dissociation constant indicates the relative acid or base properties and ionization potential for a given chemical. For example, flazasulfuron has a pK_a of 4.37 at 20 C indicating weak acid ionization by proton release and dependence on soil pH (Harper 1994; Senseman 2007). Soil characteristics influencing sorption are: composition, structure and environment (Capel et al. 2001; Harper 1994; Shuman et al. 2000). Composition determines where sorption will take place in soil, for instance, crop residues may increase solubility thus preventing penetration into the soil profile.

Clay content and type determine the cation exchange capacity (CEC) and resulting sorption rates depending on ionic charge of the herbicide (Harper 1994). Herbicide sorption rates are impacted by soil structure because soil structure influences water infiltration rates. Large influxes of water are diverted through macropores instead of smaller pores preventing time for sorption to take place (Harper 1994). Further herbicide and soil interaction is described by the organic water partitioning coefficient (K_{oc}). The K_{oc} relates the ratio of chemical mass adsorbed in soil to the mass of organic carbon based on the equilibrium concentration in solution (Harper 1994). An increase in K_{oc} decreases the mobility of an organic chemical when soils contain high amounts of organic carbon. Adsorption and mobility are inversely correlated for many herbicides (Oliveira et al. 2005; Romero et al. 2006; Sarmah and Sabadie 2002). Pronamide is considered moderately mobile (Senseman 2007) and the pronamide label cautions against application to any area that may drain onto bentgrass greens or areas of sensitive cool season grasses (Anonymous 2009b). Pronamide mobility in runoff water has been confirmed in field studies on turfgrass (Askew and Murphy 2009; Dernoeden 1995; Lange and Agamalian 1972). The physical characteristics of pronamide, however, indicate the herbicide should be less mobile than most other herbicides because the herbicide is nonionizable, has high K_{oc} values (800 to 2240) and has low water solubility (15 mg L^{-1}) (Senseman 2007). Pronamide is therefore an excellent example of the complexities related to prediction of herbicide mobility. Sulfonylurea herbicides are described as anionic weak acids with pK_a from 3 to 5; indicating low adsorption (Harper 1994; Matocha et al. 2006b; Romero et al. 2006). Flazasulfuron and trifloxysulfuron sodium have high water solubility of 2100 and 5600 g L^{-1}, respectively, and low K_{oc} of approximately 4 (Senseman 2007); indicating greater mobility than pronamide. Trifloxysulfuron sodium mobility in runoff water has been shown in cotton (*Gossypium hirsutum* L.) (Matocha et al. 2006b) and turfgrass (Askew and Murphy 2009). Flazasulfuron mobility has not been reported. Since trifloxysulfuron sodium is relatively mobile in turfgrass environments and chemically similar to flazasulfuron, mobility of flazasulfuron in runoff water should be assessed. Our objective is to determine the relative down slope movement of flazasulfuron, pronamide, and trifloxysulfuron sodium in runoff water by using perennial ryegrass injury as an indicator.

Spray drift

Herbicide drift is the movement of spray droplets to an unintended location and drift is influenced by physical and environmental conditions. Physical conditions include spray viscosity, herbicide volatility, and application equipment parameters such as ground speed, nozzle selection, and pressure (Carlsen et al. 2006a, 2006b; Jensen et al. 2001; Ramsdale and Messersmith 2001; Valcore 2008). Environmental conditions include wind speed, wind direction, temperature, and humidity (Bird et al. 2002; Capel et al. 2001; Carlsen et al. 2006a, 2006b; Ellis et al. 2003). Drift of sulfonylurea herbicides has not been fully studied. The current literature contains several studies where drift was simulated by applying low rates of glyphosate (Ellis et al. 2003; Johnson et al. 2006; Roider et al. 2008) and other herbicides (Bond et al. 2006; Lovelace et al. 2007) and a few studies where drift was assessed directly in the field via passive dosimeters (Carlsen et al. 2006a, 2006b) and bioassays (Marrs et al. 1993; Vangessel and Johnson 2005). Of these, only one study evaluated a sulfonylurea herbicide, tribenuron methyl (Carlsen et al. 2006a, 2006b).

The Office of Prevention, Pesticides, and Toxic Substances of the US Environmental Protection Agency (EPA) requires drift assessment using standard equipment for the type of pesticide, consumer formulations, and data collected either passively or by bioassay equivalent (Anonymous 1989a, 1989b). In addition to these requirements, field drift studies must test the worst case scenario within the label parameters (Anonymous 1989a, 1989b). These studies are used to determine acceptable safe distances between pesticide application and sensitive plants, animals, and people. Alternatively, the EPA will accept safe distances calculated by agDRIFT, a data base designed to model drift parameters (Anonymous 1989a, 1989b). Most pesticides labels, will include a required buffer area that specifies a nontreated zone based on the acceptable safe distance.

Table 1. Buffer zones and drift reduction restrictions for sulfonylurea herbicides registered for use in US turfgrass.

Herbicide	**Product name**	**Minimum buffer (ft)**	**Maximum buffer (ft)**	**Precautions**
Chlorsulfuron	Corsair	0	0	No specific drift precautions.
Flazasulfuron	Katana	100	100	Do not apply at wind speed below 2 mph or above 10 mph. Do not exceed boom height of 4 ft. Spray is applied with coarse or extremely coarse sprays (based on ASAE standard). Leave adequate buffer zone of 100 ft between treated area and sensitive plants.
Foramsulfuron	Revolver	0	15	Use medium spray droplets and a 15 ft buffer is suggested.
Metsulfuron	Manor	0	0	Max. wind speed of 10 mph and max. spray pressure of 240 PSI. Use "large droplet size sprays to minimize drift."
Rimsulfuron	Tranxit	0	0	Do not apply at wind speed greater than 10 mph. Nozzles that produce droplets greater than 150 to 200 microns is suggested.
Sulfosulfuron	Certainty	4	4	Do not spray within 4 ft of golf greens. Avoid nozzle and pressure combination that "will result in splatter or the generation of fine spray particles (mist)."
Trifloxysulfuron	Monument	0	25	If boom height above 2 ft use 25 ft

sodium				buffer. Use nozzles that provide medium to coarse droplets with 250 to 400 VMD.

The initial flazasulfuron label approved by EPA requires a 30-m buffer between treated turfgrass and any sensitive plants. The most common use of flazasulfuron in the US turfgrass market will be control of perennial ryegrass on overseeded bermudagrass golf fairways (Morris 2004). The average fairway is less than 60 m wide, so use of flazasulfuron would be impossible on any golf course where cool-season turfgrass is managed in roughs or surrounding areas (Beard 1973). In Virginia, for example, this label restriction would render flazasulfuron unusable on over 90% of golf courses (Barnes et al. 2006). Variations in labeled minimum buffer areas between herbicides (Table 1) are difficult to explain with current scientific literature which suggests differences in pesticide active ingredient have little impact on drift (Carlsen et al. 2006b). In terms of use patterns and bioefficacy, flazasulfuron is similar to trifloxysulfuron sodium when used on turfgrass (Harrell et al. 2005; Willis et al. 2007). The required buffer of 7.6 m on the trifloxysulfuron sodium label is acceptable considering use patterns in the turfgrass industry. The buffer of 30 m required on the current flazasulfuron label is not practical for the US turfgrass market.

In order to reduce the mandated 30-m buffer for flazasulfuron, data are needed on actual drift, runoff, and tracking. Since trifloxysulfuron sodium is most similar to flazasulfuron among herbicides used in turfgrass, it seems prudent to compare mobility of flazasulfuron with that of trifloxysulfuron sodium. Trifloxysulfuron sodium injured corn in field trials (Porterfield and Wilcut 2002), so corn seems a plausible bioassay species. Our objectives related to runoff and tracking have been discussed earlier in this introduction. Our third and final objective is to assess drift of flazasulfuron and trifloxysulfuron sodium using EPA guidelines for application conditions that match label specifications for each herbicide and determining amounts of product at various distances via a bioassay on corn heights.

RESEARCH OBJECTIVES

1. Evaluate the effects of buffer distance, post-treatment irrigation, and herbicide treatment on creeping bentgrass putting green injury from foot traffic that traversed treated areas and the adjacent putting green.
2. Determine the relative down slope movement of flazasulfuron, pronamide, and trifloxysulfuron sodium in runoff water by using perennial ryegrass injury as an indicator.
3. Assess drift of flazasulfuron and trifloxysulfuron sodium using EPA guidelines for application conditions that match label specifications for each herbicide and determining amounts of product at various distances via a bioassay on corn heights.

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Chapter 2: Creeping bentgrass (*Agrostis stolonifera*) putting green response to flazasulfuron and trifloxysulfuron sodium deposited via foot traffic

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Abstract

Although studies have shown sulfonylurea herbicides can be dislodged from treated turf by mower tires and deposited onto creeping bentgrass putting greens to cause injury, none have evaluated herbicide movement via foot traffic. Flazasulfuron is under evaluation for use in US

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turfgrass but has injured creeping bentgrass when deposited by foot traffic in Japan. Several field trials were conducted at six locations across the US to evaluate the effects of irrigation, herbicide treatment, nontreated buffer distance, and time of tracking when technicians walked through 60 m of treated turf, over nontreated buffer turf, and onto a creeping bentgrass golf putting green. Average turf injury did not exceed 2% when flazasulfuron at three rates or trifloxysulfuron sodium at two rates were dislodged from treated areas and deposited onto putting greens via foot traffic. Irrigation of treated turf eliminated injury to creeping bentgrass caused by dislodgable herbicide. When treated turf was not irrigated, injury decreased and normalized difference vegetative index (NDVI) increased with increasing buffer distance. Creeping bentgrass injury was generally highest when foot traffic occurred 1 day after treatment compared to 2 or 3 days after treatment. Data support the importance of post treatment irrigation to reduce lateral relocation of sulfonylurea herbicides like flazasulfuron and trifloxysulfuron sodium in turfgrass.

Nomenclature: Flazasulfuron; trifloxysulfuron sodium; *Agrostis stolonifera* L., creeping bentgrass, ‘Crenshaw’, ‘Penncross’; *Cynodon dactylon* L. bermudagrass 'Champion', ‘Mini Verde’, ‘Vamont’; *Lolium perenne* L., perennial ryegrass, ‘ASP6003’.

Key words: Lateral mobility, herbicide injury, tracking, turfgrass.

Introduction

Previous work with flazasulfuron, foramsulfuron, metsulfuron, rimsulfuron, and trifloxysulfuron sodium has indicated potential for all of these herbicides to move via tracking

(Barker et al. 2005, 2006; Willis and Askew 2008). Golf course superintendents have reported incidents of sulfonylurea herbicides from bermudagrass onto creeping bentgrass resulting in unacceptable injury (W.B Gallager and M. Vaughn, personal communication). Most problems on golf courses occurred when equipment used to mow creeping bentgrass traversed treated areas and returned to the creeping bentgrass or excessive rainfall occurred soon after treatment and runoff injured sensitive grasses down slope of the treated area (Askew and Murphy 2009; Barker et al. 2005, 2006; Willis and Askew 2008). Barker et al. (2005, 2006) described creeping bentgrass injury from rimsulfuron lateral relocation and elucidated irrigation regimes to wash nonabsorbed herbicide from treated leaves to mitigate the problem. Flazasulfuron was tracked more by mower tires when dew was present and high herbicide rates were applied than when leaves were dry and low rates were applied (Willis and Askew 2008). In the same study, the authors concluded that the distance of observable creeping bentgrass injury increased 0.6 m with each 10 g ai ha^{-1} increase in flazasulfuron rate. In these studies that evaluated tracking of SU herbicides, data suggest bentgrass injury can be minimized by irrigating the treated area after application, using low rates near sensitive turf, and maintaining a 1.5 to 4.5 m buffer of nontreated turf between the treated area and sensitive grasses (Barker et al. 2005, 2006; Willis and Askew 2008). It was likewise found that 93% of applied trifloxysulfuron sodium could be washed from treated cotton (*Gossypium hirsutum* L.) leaves and 91% of rinsed herbicide may be incorporated into underlying soil (Matocha et al. 2006a).

In a study from Japan, foot traffic injured creeping bentgrass after traversing treated zoysiagrass and a 25 m nontreated buffer area (ISK Bioscience, unpublished data). Based on this study, a 30-m nontreated buffer zone was specified as a requirement in the proposed US EPA label submitted for flazasulfuron. Previous work that evaluated mower traffic following treatment indicates a 5-m buffer is sufficient to prevent injury to adjacent turf (Barker et al. 2005, 2006; Willis and Askew 2008). Assuming an herbicide has been dislodged by a tire or shoe, the ability to deposit that herbicide depends on the amount of turfgrass contacted per unit distance and time after leaving the treated area. In previous work, mower tires were 0.9 m in circumference, so any given point on the tire surface will contact turfgrass once every 0.9 m (Barker et al. 2005; Willis and Askew 2008). The normal adult step is about 0.8 m and a stride is 1.5 m with uneven pressure applied from heel to toe (Winter 2009). Thus, the shoe only contacts turfgrass once every 1.5 m, so foot traffic covers greater distances with fewer contact events than mower traffic. It is reasonable to assume a greater buffer area would be needed to protect from herbicide lateral relocation via foot traffic than by mower traffic. The contribution of foot traffic to flazasulfuron lateral relocation has not been assessed in the US. Our objective is to evaluate the effects of herbicide treatment buffer distance, and post-treatment irrigation on creeping bentgrass putting green injury from foot traffic that first traversed treated areas prior to the putting green.

MATERIALS AND METHODS

Field studies were conducted in spring of 2009 at Auburn University, Clemson University, North Carolina State University, University of Tennessee, Virginia Tech, and at The Vintage Club in Indian Springs, California. Each site consisted of a creeping bentgrass putting green bordered by enough turf to allow for sufficient treated area and nontreated buffer. Studies were arranged in a randomized complete block split split plot design with four factors and a total of 108 treatments. The first factor consisted of two levels of irrigation (yes or no) and was considered the main plot in the treatment structure. The second factor consisted of six levels of herbicide treatment and were considered subplots in the analysis. The third and fourth factors comprised a factorial arrangement with nine total levels and were considered the subsubplots in the analysis. The third factor consisted of three levels of track timing including 1, 2, and 3 days after treatment (DAT). The fourth factor consisted of three levels of nontreated buffer distance including 1.5, 4.6, and 7.6 m. Irrigation for the main plot was applied at a rate of 3 mm on specified plots each morning before a tracking event. Irrigation was applied by hand wands and hose or by in-ground sprinklers depending on location. Herbicide treatments in the subplots included flazasulfuron[1] at 12, 25 and 50 g ai ha^{-1}, trifloxysulfuron sodium[2] at 18 and 30 g ai ha^{-1}, and a nontreated check. A nonionic surfactant[3] was included at 0.25% by volume with herbicide treatments. Tracking always occurred in the morning when dew was present on treated turf and after mowing the putting green. Track times are referenced as 1, 2, and 3 DAT although herbicides were applied the evening before the first morning tracking, which occurred approximately 15 hours later. Buffer distances were chosen to represent distances that may reflect reasonable regulations on a pending flazasulfuron herbicide label. Although expressed as linear distances, all researchers agreed that the number of contact events between shoes and turf were also acceptable equivalents assuming normal adult step and stride of 0.8 and 1.5 m, respectively (Winter 2009). Thus, buffer distance was replaced with number of strides. Strides established were 1, 3, and 5, where one stride is equivalent to two steps (one for each foot). A common golf shoe[4] make and model was chosen and used by all researchers. During a tracking event, each technician traversed a distance of 60 m (40 strides) of treated turfgrass immediately before traversing the required nontreated buffer turf and stepping onto the putting green. Once on the putting green, the technician would step each foot five times in place to simulate the setup for a golf putt and help insure dislodged herbicide had ample opportunity to be deposited in the plot of interest. While exiting the putting green, care was taken not to traverse any other plots. After exiting the green, shoes were removed and thoroughly cleaned before entering the next treatment.

Data included visually-estimated creeping bentgrass color and injury and creeping bentgrass normalized difference vegetation index (NDVI) assessed using the same make and model analyzer[5] at each location. NDVI is the ratio of near infrared to infrared reflectance from plant tissue, which can be correlated to general plant health. Creeping bentgrass color was rated on a scale of 1 to 9 with 9 being excellent color and 1 being no green color and creeping bentgrass injury was rated on a scale of 0 to 100% with 0% being no injury and 100% being dead turf. Data were collected at trial initiation and weekly for 4 WAT. Values were subjected to analysis of variance and appropriate means separated Data were considered homogenous based on the distribution of plotted residuals. Furthermore, arcsine square-root or log transformation was evaluated but did not improve data homogeneity. Due to the number of treatments and limited putting green space, treatments were not replicated within each location, rather, the six locations were considered replication in the analysis. All data were subjected to analysis of variance to test for appropriate interactions and main effects with partitioning appropriate for the split split plot treatment arrangement (SAS 1998). Data were pooled if interactions were not significant. Means were separated using Fisher's Protected LSD at $P = 0.05$.

RESULTS AND DISCUSSION

Putting Green Injury

The three- and four-way interactions of irrigation, herbicide treatment, tracking time, and buffer distance were not significant ($P > 0.05$). Data from the significant interactions of irrigation by buffer distance ($P < 0.001$) and irrigation by track time ($P < 0.05$) are shown in table 1. Lack of herbicide treatment significance was surprising since a nontreated check is among the levels of herbicide treatment. This factor is likely insignificant due to variability in treatment response between locations (replications). At some locations, visual symptoms were seldom observed from any treatment while footprints were noted following herbicide treatment at other locations. Generally, injury from foot traffic on putting greens at various locations was either not detected or considered acceptable. With low levels of injury coupled with location to location variability in herbicide treatment response, trends in other significant effects were only detectable when averaged over herbicide treatments. Of the 1944 visual plot observations in these studies, only three plots were injured greater than 10% (data not shown). The highest numeric injury was 20% and occurred in one instance at North Carolina State University (data not shown). Injury between 5 and 10% occurred more frequently at Clemson University, North Carolina State University, and Virginia Tech. Injury seldom occurred at Auburn University,

University of Tennessee, or at the golf course in California. Thus, injury shown in table 1 is always less than 1%. It must be noted that although these levels of injury are statistically significant and are expressed to two significant digits out of necessity, they are not biologically significant. The trends exhibited by these data, however, seem biologically relevant. In 15 of 18 comparisons in Table 1, applying irrigation each morning after treatment significantly decreased turf injury from tracking. Other research has noted the importance of post treatment irrigation for rinsing nonabsorbed herbicide from turf foliage (Barker et al. 2006; Matocha et al. 2006a; Willis and Askew 2008). When turf was not irrigated after treatment, creeping bentgrass injury increased with each decrease in buffer distance (Table 1). When turf was irrigated after treatment, significant creeping bentgrass injury did not occur (Table 1). When turf was tracked 1 and 2 DAT, creeping bentgrass was injured more than when turf was tracked 3 DAT. When turf was tracked 3 DAT, significant creeping bentgrass injury did not occur (Table 1).

Putting Green NDVI

Trends that occurred in visual injury were mirrored by trends in NDVI. The interactions of irrigation by buffer distance ($P < 0.001$) and irrigation by tracking time ($P < 0.001$) were significant for creeping bentgrass NDVI to the exclusion of higher-level interactions (Table 2). In 5 of 18 comparisons, irrigation applied to treated turf each morning increased NDVI compared to nontreated turf. In all other cases, no differences in NDVI occurred between irrigated and nonirrigated plots (Table 2). When treated turf was irrigated, significant differences in NDVI were not observed between buffer distances or tracking times, except at 2 WAT (Table 2). When treated turf was not irrigated, NDVI decreased as buffer distance decreased (Table 2). At 2 WAT, foot traffic on treated turf 1 DAT injured creeping bentgrass more than foot traffic on treated turf 2 and 3 DAT (Table 2). The number of irrigation events applied to treated turf increases concurrently with tracking time as the turf was irrigated each morning. Increasing the number of irrigation events can decrease the amount of pesticide available to be dislodged from leaves. Dislodgable residues of isazofos were reduced two- to three-fold after the first irrigation and decreased linearly as the number of irrigation events increased (Clark et al. 2000). Clark et al. (2000) also noted that increased irrigation rates from 6 to 12 mm decreased the amount of dislodgable isazofos residue. Irrigation rate in the current study was 3 mm, so increased irrigation rate could protect putting greens from foot traffic even more than the current study. Since irrigation decreased visual injury (Table 1) and increased NDVI (Table 2), it seems reasonable to assume irrigating treated turf prior to a tracking event will effectively reduce herbicide lateral mobility via tracking. Rimsulfuron was shown to persist on perennial ryegrass and annual bluegrass foliage for 3 d (Barker et al. 2006) and most sulfonylurea herbicides are not completely absorbed by plants (Askew and Wilcut 2002; Matocha et al. 2006a and 2006b; McElroy and Yelverton 2004; Troxler et al. 2007). Irrigation has decreased tracking injury to creeping bentgrass in other studies (Barker et al. 2005; Willis and Askew 2008). This study was conducted on a wide range of treated and buffer turf indicative of types found on US golf courses. Data from this study indicates that foot traffic may dislodge flazasulfuron or trifloxysulfuron sodium when treated turfgrass is not irrigated prior to the tracking event. The threat of foot traffic is minimal as injury in the current study was always acceptable and can be prevented by irrigating treated turf prior to tracking or setting a buffer distance of 7.6 m from golf putting greens.

SOURCES OF MATERIALS

[1].Flazasulfuron 25WP, ISK Biosciences Corporation, 2237 Haden Road, Houston, TX 77015-6449, USA.

[2] Monument™ 75DF. Syngenta Crop Protection, P.O. Box 18300,Greensboro, NC 27419, USA.

[3] Chem-Stik Nonionic Spreader-Sticker, Precision Laboratories, Inc., 1429 S. Shields Drive, Waukegan, IL 60085 USA

[4] Nike™ SP8 Tour Saddle Nike USA, Inc. One Bowerman Drive, Beaverton, OR 97005 USA

[5] FieldScout™ TCM 500 NDVI Turf Color Meter, Spectrum Technologies, Inc., 12360 South Industrial Dr. East - Plainfield, Illinois 60585 USA

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Table 1: Values of irrigation by buffer distance and irrigation by time of tracking on visually-estimated creeping bentgrass putting green injury following foot traffic through treated turfgrass (averaged over five treatments including three rates of flazasulfuron and two rates of trifloxysulfuron sodium)[a].

	1 WAT[b]		2 WAT		3 WAT	
Variable	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated
	%					
Stride [d]						
1	0.00* [c]	0.37*	0.00*	2.00*	0.00*	0.80*
3	0.00	0.28	0.00*	1.20*	0.01*	0.60*
5	0.01	0.17	0.00*	0.79*	0.00*	0.40*
LSD (0.05)	NS	0.10	NS	0.60	NS	0.17
Time of tracking (DAT)						
1	0.00*	0.26*	0.00*	0.01*	0.00*	0.60*
2	0.01*	0.38*	0.00*	0.10*	0.01*	0.90*

3	0.00	0.17	0.00*	0.01*	0.00*	0.20*
LSD (0.05)	NS	NS	NS	NS	NS	0.44

[a] Averaged over treatments including flazasulfuron at 12, 25, and 50 g ai ha^{-1} and trifloxysulfuron sodium at 18 and 3 g ai ha^{-1}*

[b] Abbreviations: DAT, days after treatment; LSD, least significant difference at P = 0.05; WAT, weeks after treatment.

[c] A '*' indicates significant difference between irrigated and nonirrigated treatments at a given buffer distance or time of tracking.

[d] One stride is one contact per foot.

Table 2: Interactions of irrigation by buffer distance and irrigation by time of tracking on normalized difference vegetation index (NDVI) of creeping bentgrass putting green turf following foot traffic through treated turfgrass (averaged over five treatments including three rates of flazasulfuron and two rates of trifloxysulfuron sodium)[a].

	1 WAT[b]		2 WAT		3 WAT	
Variable	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated
	NDVI					
Stride[d]						
1	0.7420*[c]	0.7268*	0.7388*	0.7237*	0.7576	0.7538
3	0.7439	0.7430	0.7399	0.7388	0.7590	0.7649
5	0.7312	0.7480	0.7393	0.7425	0.7688*	0.7583*
LSD (0.05)	NS	0.0091	NS	0.0086	NS	0.0089
Time of tracking (DAT)						
1	0.7406	0.7401	0.7330	0.7346	0.7632*	0.7530*
2	0.7320	0.7357	0.7432	0.7374	0.7580	0.7617

3	0.7445	0.7420	0.7418*	0.7329*	0.7639	0.7625
LSD (0.05)	NS	NS	0.0054	NS	NS	0.0055

[a] Averaged over treatments including flazasulfuron at 12, 25, and 50 g ai ha^{-1} and trifloxysulfuron sodium at 18 and 30 g ai ha^{-1}*

[b] Abbreviations: DAT, days after treatment; LSD, least significant difference at P = 0.05; NDVI, normalized difference vegetative index; WAT, weeks after treatment.

[c] A '*' indicates significant difference between irrigated and nonirrigated treatments at a given buffer distance or time of tracking.

[d] One stride is one contact per foot.

Chapter 3: Turfgrass Response to Flazasulfuron and Trifloxysulfuron Sodium Deposited by Runoff Water

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Abstract

Flazasulfuron is a new herbicide registered for use in warm-season turfgrass and concerns have been raised over herbicide mobility in surface runoff water. Studies were conducted in Blacksburg, VA and Charlottesville, VA in 2004 to evaluate injury to perennial ryegrass down slope of plots treated with transition-assisting herbicides. At Farmington Country Club (FCC), soil was more saturated and a natural rainfall increased the rate of runoff and subsequent severity of perennial ryegrass injury below treated plots. Flazasulfuron at 52 g a.i. ha^{-1} and pronamide consistently injured perennial ryegrass more than trifloxysulfuron sodium or lower rates of flazasulfuron. Flazasulfuron at 52 g ha^{-1} and pronamide caused visible injury to perennial ryegrass 10 to 16 m below treated plots at FCC and 3 m below plots at another location where soil was less saturated and irrigation was applied at a slower rate. Based on perennial ryegrass injury, flazasulfuron at the rates tested can be considered equivalent or more mobile than

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trifloxysulfuron sodium and equivalent or less mobile than pronamide when subjected to excessive irrigation or rainfall soon after application to saturated soils. Precautions should be taken to avoid application of these herbicides to saturated soils and apply when rainfall is not expected for sufficient time to rinse turfgrass foliage and incorporate nonabsorbed herbicide into soil via light irrigation.

Nomenclature: Flazasulfuron; pronamide; trifloxysulfuron sodium; *Cynodon dactylon* L. bermudagrass 'Vamont'; *Lolium perenne*, perennial ryegrass, 'Prosport', 'Transist'.

Key words: Lateral mobility, herbicide injury, turfgrass.

Introduction

Flazasulfuron is safe for use in bermudagrass [*Cynodon dactylon* (L.) Pers.] and zoysiagrass (*Zoysia japonica* Steud.) and was conditionally registered in the United States for use on these turfgrasses in 2007 (Tompkins 2007). Flazasulfuron is similar in herbicidal activity and turfgrass safety to foramsulfuron, rimsulfuron, and trifloxysulfuron sodium, which were all labeled in US turfgrass since 2001 (Senseman 2007). These herbicides are commonly used to transition overseeded bermudagrass back to a monoculture by controlling fall seeded perennial ryegrass the following spring (Harrell et al. 2005; Rolfe et al. 2007). Bermudagrass is often over seeded with perennial ryegrass in cool climates to increase aesthetics in the winter months and requires ryegrass control in the spring for optimal bermudagrass development (Beard 1973; Yelverton 2005). In fine turf, spring applications of flazasulfuron control perennial ryegrass in bermudagrass fairways and athletic fields faster and more effectively than other products currently available. (Rolfe et al. 2007). Although SU herbicides like flazasulfuron bring several potential benefits to turfgrass markets, there are also several concerns related to using these herbicides in turfgrass areas. For many plant species, SU herbicides can cause phytotoxicity or death at less than 1 g ai/ha^{1-} (Senseman 2007) indicating small quantities of active ingredient are required to cause problems if herbicide moves in the environment.

Herbicide sorption rates are impacted by soil structure because soil structure influences water infiltration rates. Large influxes of water are diverted through macropores instead of smaller pores preventing time for sorption to take place (Harper 1994). Further herbicide and soil interaction is described by the organic water partitioning coefficient (K_{oc}). The K_{oc} relates the ratio of chemical mass adsorbed in soil to the mass of organic carbon based on the equilibrium concentration in solution (Gouy et al. 1999; Harper 1994). An increase in K_{oc} decreases the mobility of an organic chemical when soils contain high amounts of organic carbon. Adsorption and mobility are inversely correlated for many herbicides (Oliveira et al. 2005; Romero et al. 2006; Sarmah and Sabadie 2002). Pronamide is considered moderately mobile (Senseman 2007) and the pronamide label cautions against application to any area that may drain onto bentgrass greens or areas of sensitive cool season grasses (Anonymous 2009). Pronamide mobility in runoff water has been confirmed in field studies on turfgrass (Askew and Murphy 2009; Dernoeden 1995; Lange and Agamalian 1972). The physical characteristics of pronamide, however, indicate the herbicide should be less mobile than most other herbicides because the herbicide is nonionizable, has high K_{oc} values (800 to 2240) and has low water solubility (15 mg L^{-1}) (Senseman 2007). Pronamide is therefore an excellent example of the complexities related to prediction of herbicide mobility. Sulfonylurea herbicides are described as anionic weak acids with pK_a from 3 to 5; indicating low adsorption (Harper 1994; Matocha et al. 2006b; Romero et al. 2006). Flazasulfuron and trifloxysulfuron sodium have high water solubility of 2100 and 5600 g L^{-1}, respectively, and low K_{oc} of approximately 4 (Senseman 2007); indicating greater mobility than pronamide. Trifloxysulfuron sodium mobility in runoff water has been observed in cotton (*Gossypium hirsutum* L.) (Matocha et al. 2006b) and turfgrass (Askew and Murphy 2009). Flazasulfuron mobility has not been reported. Since trifloxysulfuron sodium is relatively mobile in turfgrass environments and chemically similar to flazasulfuron, mobility of flazasulfuron in runoff water should be assessed. Our objective is to determine the relative down slope movement of flazasulfuron, pronamide, and trifloxysulfuron sodium in runoff water by using perennial ryegrass injury as an indicator.

MATERIALS AND METHODS

Studies were conducted in Blacksburg, VA at the Turfgrass Research Center and Charlottesville, VA on a fairway at Farmington Country Club on overseeded bermudagrass maintained at 1.5 cm to evaluate injury to perennial ryegrass down slope of plots treated with transition-assisting herbicides. ‘Vamont’ bermudagrass was overseeded with ‘Prosport’ perennial ryegrass in Blacksburg and ‘Transist’ intermediate ryegrass in Charlottesville. Soil was a Groseclose loam (clayey, mixed, mesic, Typic Hapludalfs) with 2% organic matter and pH 6.5 in Blacksburg. A soil survey was not available for the fairway area of Farmington Country Club but soil analysis indicated it was a sandy loam with 2.1% organic matter and pH 6.8. Trials were arranged as randomized complete block designs with three replications on May 19, 2004 in Charlottesville, VA, and September 16, 2004 in Blacksburg, VA.

One by four meter plots were treated with flazasulfuron[1] at 9, 26 and 52 g a.i. ha^{-1}, pronamide[2] at 1120 g a.i. ha^{-1}, and trifloxysulfuron sodium[3] at 17 g a.i. ha^{-1}. Each plot was oriented such that sideward slope was less than 1% and down slope was between 7 and 11%. At application, soil was between 19 and 24% moisture at Blacksburg, VA in 2004 and between 28 and 38% moisture in Charlottesville, VA in 2004. Treated plots were allowed to dry for 2 hours at each location and irrigation was applied over a period of 8 hours with repeated passes of walking irrigators[4] at Blacksburg and over 4 hours with Toro sprinkler heads for the first 30 minutes followed by a natural rainfall event at Charlottesville. Containers were placed at the top edge of each plot during irrigation or rainfall and plots received between 50 and 70 mm of water on all plots at each location. Perennial ryegrass phytotoxicity was visually estimated in a m^2 area below treated plots. In addition, the distance of perceived perennial ryegrass injury below treated plots was measured.

Data were converted to the log or the arc sine of the square root and plotted residuals were compared to normal data to evaluate homogeneity of variance. Where transformation was required to improve variance homogeneity, nontransformed means are presented for clarity. Data were subjected to analysis of variance with the two trial locations as a random variable. Treatment effects were tested with the sum of squares from the treatment by location interaction (McIntosh, 1983). Where location interactions did not occur, data were pooled over locations; otherwise data from different locations were presented separately. Means were separated using Fisher's Protected LSD at P = 0.05.

RESULTS AND DISCUSSION

Injury Severity

Analysis of variance on percentage visually-estimated perennial ryegrass injury at various distances between 0 and 1 m below treated plots indicated the interaction of location and treatment was significant ($P<0.001$). Therefore, data were separated by location for discussion (Table 1). This interaction likely occurred due to increased herbicidal injury at FCC compared to TRC. At FCC, a natural rainfall occurred and the required amount of water was received in half the time required at TRC. In addition, soil was more saturated at FCC (28 to 38% moisture) than at TRC (19 to 24% moisture) prior to study initiation. Studies have shown that herbicide mobility is positively correlated with rate of runoff (Gouy et al. 1999; Smith et al. 2002). The rate of runoff increases as soil saturation increases (Armbrust and Peeler, 2002; Müller et al. 2005; Smith et al. 2002) and as the rate of irrigation or rainfall increases (Müller et al. 2004). When assessing the area 0 to 15 cm below each plot, all herbicides injured perennial ryegrass at least 93% at FCC while flazasulfuron at 52 g ha^{-1} and pronamide injured perennial ryegrass more than flazasulfuron at 9 g ha^{-1} and trifloxysulfuron sodium at TRC (Table 1). At TRC, the same trend was evident at 16 to 30 cm and 31 to 45 cm below treated plots where the highest rate of flazasulfuron and pronamide injured perennial ryegrass more than trifloxysulfuron sodium and lower rates of flazasulfuron (Table 1). Trifloxysulfuron sodium was applied at the low end of suggested use rates in this study but injured perennial ryegrass equivalent to pronamide under similar conditions at only one of three locations when applied at higher rates (Askew and Murphy 2009). It should be noted that the severity of herbicide injury does not necessarily indicate the likeliness of herbicides to move or to cause injury symptoms in neighboring grasses.

Pronamide controls perennial ryegrass slower than flazasulfuron and trifloxysulfuron (Horgan and Yelverton 2001; Johnson 1976) so the severity of injury from pronamide would be expected to be less than that of the sulfonylurea herbicides at 4 weeks after treatment (WAT). Evidence of slower pronamide activity is reflected in perennial ryegrass control inside treated plots at TRC where pronamide only controlled perennial ryegrass 50% 4 WAT compared to 92% or more control from sulfonylurea herbicides (Table 2).

Distance of Observable Injury

The location by treatment interaction was also significant for distance of observable herbicide injury ($P < 0.005$). Flazasulfuron at 52 g ha^{-1} injured perennial ryegrass 16 m below treated plots at FCC and further than all other treatments (Table 2). This rate, however, is three to six times that needed to control perennial ryegrass during bermudagrass post-dormancy transition (Harrell et al. 2007; Hutto et al. 2008; Rolfe et al. 2007). This high rate of flazasulfuron injured perennial ryegrass only 3 m below treated plots at TRC (Table 2). Flazasulfuron at 9 g ha^{-1} injured perennial ryegrass to a distance of 6 and 1 m below treated plots at FCC and TRC, respectively and equivalent to trifloxysulfuron sodium (Table 2). In similar studies, trifloxysulfuron sodium at 32 g ha^{-1} injured perennial ryegrass at distances greater than that observed for metsulfuron and rimsulfuron but less than that observed for pronamide (Askew and Murphy 2009). Since flazasulfuron injured perennial ryegrass at distances equal or greater to pronamide in the current study, it may be assumed that flazasulfuron is more likely to injure perennial ryegrass than other sulfonylurea herbicides used in turfgrass when deposited by runoff water. Data suggest flazasulfuron rate should be reduced when treating areas that are up slope of sensitive grasses. Demonstrations in Florida indicate these herbicides are less apt to cause perennial ryegrass injury down slope of treated areas if rainfall or irrigation is withheld for 4 to 24 hours after treatment (HAT) (Unruh 2004). Likewise, higher amounts of MCPP were detected in runoff water for the first 24 HAT and detected amounts decreased over 99% after 2 weeks (Watschke et al. 2000). Matocha et al. (2006a) found 93% of applied trifloxysulfuron sodium was washed from cotton leaves and 9% of rinsate was found in runoff water while 91% infiltrated the soil profile within the first few minutes. It is generally recommended to irrigate treated areas lightly 4 HAT to aid in the incorporation of herbicide into the turfgrass organic matter layer (Barker et al. 2006; Smith et al. 2002; Unruh 2004). By applying herbicides to near-saturated soils and irrigating two hours later, a worst-case scenario was tested in the current study. The location interaction in this study suggests that herbicide mobility increases with increasing soil saturation and rate of irrigation or rainfall. Based on perennial ryegrass injury, flazasulfuron at the rates tested can be considered equivalent or more mobile than trifloxysulfuron sodium and equivalent or less mobile than pronamide when subjected to excessive irrigation or rainfall soon after application to saturated soils. Precautions should be taken to avoid application of these herbicides to saturated soils and apply when rainfall is not expected for sufficient time to rinse turfgrass foliage and incorporate nonabsorbed herbicide into soil via light irrigation.

SOURCES OF MATERIALS

[1].Flazasulfuron 25WP, ISK Biosciences Corporation, 2237 Haden Road Houston, TX 77015-6449, USA.

[2] Kerb™ 25WP, Dow AgroSciences LLC, 207 Wood Duck Loop, Mooresville, NC 28117, USA.

[3] Monument™ 75DF. Syngenta Crop Protection, P.O. Box 18300,Greensboro, NC 27419, USA.

[4] RainCoach™ Self Propelled Traveling Sprinkler, Storm Manufacturing Group, Inc., 23201 Normandie Ave., Torrance, CA 90501, USA.

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Table 1: Percentage visually-estimated perennial ryegrass injury at 0-15, 16-30, and 31-45 cm down slope of 1 m by 4 m plots treated with various herbicides then subjected to 50-70 mm water via rainfall or irrigation at Farmington Country Club (FCC) and the Turfgrass Research Center (TRC)[a] four weeks after treatment.

		Distance below treated plot					
		0-15 (cm)		16-30 (cm)		31-45 (cm)	
Herbicide	Rate	FCC	TRC	FCC	TRC	FCC	TRC
	(g ai ha^{-1})	%					
Flazasulfuron	9	100	20	90	9	87	2
Flazasulfuron	26	93	30	93	17	91	10
Flazasulfuron	52	100	53	100	43	100	32
Pronamide	1120	100	42	80	37	80	28
Trifloxysulfuron	17	93	12	93	2	90	0
LSD (0.05)		NS	17	15	16	13	12

[a] Abbreviations: FCC, Farmington Country Club; LSD, least significant difference at P = 0.05; TRC, Turfgrass Research Center.

Table 2. Percentage visually estimated perennial ryegrass control inside treated plots and distance of observed perennial ryegrass phytotoxicity down slope of treated plots 4 weeks after treatment at two locations.

		Control in treated plot		Distance of visual injury	
Herbicide	Rate	FCC	TRC	FCC	TRC
	(g ai ha^{-1})	—— % ——		—— m ——	
Flazasulfuron	9	100	95	6	1
Flazasulfuron	26	100	98	7	2
Flazasulfuron	52	100	99	16	3
Pronamide	1120	100	50	10	3
Trifloxysulfuron	17	98	92	5	1
LSD (0.05)		NS	7	4	1

[a] Abbreviations: FCC, Farmington Country Club; LSD, least significant difference at P = 0.05; TRC, Turfgrass Research Center.

Chapter 4: Field Assessment of Flazasulfuron and Trifloxysulfuron Sodium Drift Using a Corn (*Zea Mays*) Bioassay

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Abstract

Pesticide drift continues to be a problem for sprayable plant protection products. Flazasulfuron recently received a conditional registration from the United State Environmental Protection Agency that specified a 30-m nontreated buffer between treated areas and sensitive plants. This buffer would make most intended uses of flazasulfuron in warm-season turfgrass impossible due to neighboring cool-season turfgrass that are considered "sensitive plants." Assessment of drift in field conditions is required to replace model-predicted buffer restrictions. Studies were conducted to assess drift of flazasulfuron and a similar herbicide, trifloxysulfuron sodium, in field conditions using conventional turfgrass spray equipment and maximum boom height and droplet size specified on product labels. Herbicides were applied perpendicular to a 6.4 to 9.7 km hr^{-1} wind and corn plants were placed at distances between 0 and 30.5 m down wind. A bioassay based on corn height reduction indicated trifloxysulfuron sodium reduced corn height

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more than flazasulfuron. Herbicide drift was not detected beyond 4.6 m down wind of the application. Data suggest a 7.6 m buffer area should sufficiently protect against flazasulfuron drift.

Nomenclature: Flazasulfuron; trifloxysulfuron sodium; corn (*Zea mays* L.) ‘Honey Select’ and ‘Pioneer 35R25’.

Key words: Buffer, Spray drift, Turfgrass.

Introduction

Flazasulfuron belongs to the sulfonylurea (SU) herbicide class of chemistry which contains over 20 unique compounds. Flazasulfuron is safe for use in bermudagrass [*Cynodon dactylon* (L.) Pers.] and zoysiagrass (*Zoysia japonica* Steud.) and was conditionally registered in the United States for use on these turfgrasses in 2007 (Tompkins 2007). Flazasulfuron is similar in herbicidal activity and turfgrass safety to foramsulfuron, rimsulfuron, and trifloxysulfuron sodium, which were all labeled in US turfgrass since 2001 (Senseman 2007). These herbicides are commonly used to transition overseeded bermudagrass back to a monoculture by controlling fall seeded perennial ryegrass (*Lolium perenne* L.) the following spring (Harrell et al. 2005; Rolfe et al. 2007). Although SU herbicides like flazasulfuron bring several potential benefits to turfgrass markets, there are also several concerns related to using these herbicides in turfgrass areas. For many plant species, SU herbicides can cause phytotoxicity or death at less than 1 g ai/ha^{1-} (Senseman 2007) indicating that very small quantities of active ingredient are all that is required to cause problems if an herbicide moves from the target area.

Drift of SU herbicides has not been fully studied. The current literature contains several studies where drift was simulated by applying low rates of glyphosate (Ellis et al. 2003; Johnson et al. 2006; Roider et al. 2008) and other herbicides (Bond et al. 2006; Lovelace et al. 2007) and a few studies where drift was assessed directly in the field via passive dosimeters (Carlsen et al. 2006a, 2006b) and bioassays (Marrs et al. 1993; Vangessel and Johnson 2005). Of these, only one study evaluated a SU herbicide, tribenuron methyl (Carlsen et al. 2006a, 2006b). The Office of Prevention, Pesticides, and Toxic Substances of the US Environmental Protection Agency (EPA) requires drift assessment using standard equipment for the type of pesticide, consumer formulation with data collected either passively or by bioassay equivalent (Anonymous 1989a, 1989b). In addition to these requirements, field drift studies must test the worst case scenario within the label parameters (Anonymous 1989a, 1989b). These studies are used to determine acceptable safe distances between pesticide application and sensitive plants, animals, and people. Alternatively, the EPA will accept safe distances calculated by agDRIFT, a data base designed to model drift parameters (Anonymous 1989a, 1989b). Many pesticides labels will include a required buffer area that specifies a nontreated zone based on the acceptable safe distance.

The initial flazasulfuron label approved by EPA requires a 30-m buffer between treated turfgrass and any sensitive plants. The most common use of flazasulfuron in the US turfgrass market will be control of perennial ryegrass on overseeded bermudagrass golf fairways (Morris

2004). The average fairway is less than 60 m wide, so the use of flazasulfuron would be impossible on any golf course where cool-season turfgrass is managed in roughs or surrounding areas (Beard 1973). In Virginia, for example, this label restriction would render flazasulfuron unusable on over 90% of golf courses (Barnes et al. 2006). Variations in labeled minimum buffer areas between herbicides are difficult to explain with current scientific literature which suggests differences in pesticide active ingredient have little impact on drift (Carlsen et al. 2006b). In terms of use patterns and bioefficacy, flazasulfuron is similar to trifloxysulfuron sodium when used on turfgrass (Harrell et al. 2005; Willis et al. 2007). The required buffer of 7.6 m on the trifloxysulfuron sodium label is acceptable considering use patterns in the turfgrass industry. The buffer of 30 m required on the current flazasulfuron label is not practical for the US turfgrass market.

In order to reduce the mandated 30-m buffer for flazasulfuron, data are needed on actual drift. Since trifloxysulfuron sodium is most similar to flazasulfuron among herbicides used in turfgrass, it seems prudent to compare mobility of flazasulfuron with that of trifloxysulfuron sodium. Trifloxysulfuron sodium injured corn in field trials (Porterfield and Wilcut 2002), so corn seems a plausible bioassay species. Our objective is to assess drift of flazasulfuron and trifloxysulfuron sodium using EPA guidelines for application conditions that match label specifications for each herbicide

MATERIALS AND METHODS

Two field and bioassay studies were conducted at the Glade Road Research Facility in Blacksburg, VA in 2008 and 2009. 'Pioneer 35R25' field corn in 2008 and 'Honey Select' sweet corn seeds in 2009 were planted in 10-cm square pots filled with potting soil[1] and thinned to one plant per pot after emergence. Plants were grown in a greenhouse maintained at 30 C with a 14 h photoperiod and 200 µmoles m^{-2} sec^{-1} photosynthetically active radiation supplied with sodium halide lights. After two weeks, plant sizes were recorded and the study initiated. The drift study was established as a randomized complete block split plot design with two herbicide main plots and six distance-from-target subplots. Treatments were replicated in time for a total of five replications and four plants labeled to serve as subplots within each replication. The herbicide main plots included flazasulfuron applied at 52 g a.i. ha^{-1} and trifloxysulfuron sodium applied at 30 g a.i. ha^{-1}. Herbicides were applied in 407 L ha^{-1} using a commercial turf sprayer[2] operated at 4.8 km h^{-1} and 276 kPa. Turbo Teejet TTVP 11004 spray nozzles were used with flazasulfuron to provide coarse to very coarse spray droplets as directed in the herbicide label[3]. Trifloxysulfuron was applied with Teejet XR 11004 flat fan spray nozzles to provide medium to coarse spray droplets as directed in the herbicide label[4]. Herbicides were applied to a ‘Riviera’ bermudagrass research plot mown to 1.3 cm. The spray boom was positioned 61 cm above target turfgrass for herbicide applications. The turf sprayer has a boom width of 5.6 m and was operated perpendicular to prevailing wind direction. Plants were placed downwind along a transect parallel to wind direction and perpendicular to the direction of the sprayer. The first plants were located at the down-wind edge of the spray boom and labeled as 0 m from application. Subsequent plants were then placed 1.52, 4.57, 7.62, 15.24, and 30.48 m from the first plants. Wind speed and direction were determined using wind meters[5] and neutrally buoyant balloons. Two technicians located near the spray area monitored wind speed. When wind speed reached 6.4 to 9.7 km hr^{-1}, a neutrally-buoyant balloon was then released to determine wind direction. The time required for balloons to travel between known points was used to validate wind current speed. The sprayer was operated when wind speeds measured between 6.4 to 9.7 km hr^{-1} and wind direction was within five degrees deviation from the plant location transect. After spraying, plants were collected and returned to the greenhouse where placement was randomized. Concurrently, a bioassay was conducted to assess corn height response to herbicide rates. Eleven rates of flazasulfuron and trifloxysulfuron sodium were applied to five replicates each containing four subsamples for a total of 20 plants treated with each herbicide rate. These plants were sprayed in a track sprayer[6] using an 8001E flat fan spray nozzle operated at 2.3 km hr^{-1} to supply 281 L ha^{-1} spray solution. Herbicide rates were based on maximum labeled rates and all treatments included nonionic surfactant[7] at 0.25% by volume. Bioassay corn plants were returned to the greenhouse and randomized amongst the field drift study plants. Height measurements were taken at weekly intervals for three weeks after treatment (WAT). At 3 WAT, plants were harvested at soil level and total dry shoot biomass was measured.

In the second study repetition, all dead plants were discarded in error and dry biomass was not assessed. It was decided that too much data were missing to analyze dry biomass so only corn plant heights were used in the study. Data were tested for homogeneity of variance prior to statistical analysis. Analysis of variance (ANOVA) was performed on corn plant heights at 3

WAT and on the percent reduction in plant height compared to nontreated corn based on the following equation (Equation 1):

$$Y_{\Delta} = (1 - (H_{\alpha}-H_{\beta})/H_{\varphi})) * 100 \qquad [1]$$

where Y_{Δ} is percent reduction in plant height, H_{α} is the initial plant height in cm before treatment, H_{β} is the plant height in cm 3 WAT, and H_{φ} is the average change in plant height in nontreated pots. Herbicide rates ranged from 0 to 52 g ha-1 for flazasulfuron and 0 to 30 g ha-1 for trifloxysulfuron sodium and prevented comparison of herbicides. Therefore, rates were converted to a percentage of full rate prior to analysis.

Linear, quadratic, and higher-order polynomial effects of herbicide rate were tested by partitioning sums of squares (Draper and Smith 1981). Year was considered a random variable, and main effects or interactions were tested by the error associated with the appropriate interaction with year (McIntosh 1983). Nonlinear models were used if ANOVA indicated higher-order polynomial effects of herbicide rate were more significant than linear or quadratic effects. Iterations were performed to determine parameter estimates with least sums of squares for all nonlinear models using the Gauss-Newton method via PROC NLIN in SAS (SAS 1998). The relationship between herbicide rate and percent reduction in plant height was fitted to the rectangular hyperbola equation (Equation 2) (Cousens 1988).

$$Y_{\Delta} = iR/((1+iR/A) \qquad [2]$$

Estimated percent height reduction (Y_Δ) is based on a percent reduction of plant height over a 3 week period compared to nontreated corn, A is the asymptote for plant height reduction, R is the herbicide rate expressed as a percentage of full rates, and i is the plant height reduction per unit herbicide rate as herbicide rate approaches zero.

Coefficients of determination (R^2) were calculated for all regressions. For linear equations, R^2 values were calculated as 100 times the ratio of regression sum of squares ($\sum(\hat{Y}-\overline{Y})^2$) to corrected total sum of squares ($\sum(Y_i-\overline{Y})^2$) (Equation 3).

$$R^2{}_{linear} = 100 \times \frac{\sum(\hat{Y}-\overline{Y})^2}{\sum(Y_i-\overline{Y})^2} \qquad [3]$$

In equation 3, regression sum of squares measures the variation that can be ascribed to the fitted line, and corrected total sum of squares measures total variation about the mean (Draper and Smith 1981).

When a nonlinear equation was fit to the data, an approximate R^2 value ($R^2{}_{nonlinear}$) (Draper and Smith 1981; Jasieniuk et al. 1999) was obtained by subtracting the ratio of residual sum of squares to corrected total sum of squares from one (Equation 4).

$$R^2{}_{nonlinear} = 1 - \frac{\text{Residual sum of squares}}{\text{Corrected total sum of squares}} \qquad [4]$$

Residual sum of squares can be attributed to that variation not explained by the fitted line. The R^2 and residual mean squares (RMS) were used to determine goodness of fit to nonlinear models.

RESULTS AND DISCUSSION

Bioassay

The interaction of year by herbicide by rate was significant ($P < 0.001$) for percentage reduction in corn height 3 WAT (Figures 1 and 2). The year interaction is probably due to inconsistency of flazasulfuron effects on corn height between years. Flazasulfuron rate was poorly correlated to corn height reduction in 2008 (Figure 1). Linear, quadratic, and higher order effects were all significant ($P < 0.05$) but iterations to determine least sum of squares for the hyperbolic trend line (Equation 2) would not converge. Therefore, the linear trend line was fit to the data. Although significant, the trend line has a poor correlation coefficient of 0.25 (Figure 1). In 2009, flazasulfuron rates exhibited a hyperbolic trend for corn height reduction with a high correlation of 0.94 (Figure 2). Differences in corn response to flazasulfuron rates between years is probably due to differences in corn varieties and germination rates between years. In 2008, 'Pioneer 35R25' was obtained from cold storage at Virginia Tech and germination was sporadic; leading to variable plant sizes. In 2009, 'Honey Select' sweet corn was purchased from a local supplier and had uniform germination and plant sizes. Variable plant sizes and differential tolerance to flazasulfuron between varieties probably caused the variability in corn height reductions seen in 2008 (Figure 1). Trifloxysulfuron sodium rates were highly correlated to corn height reductions both years when fit to the hyperbolic trend line (Equation 2) (Figures 1 and 2). Trifloxysulfuron sodium has been shown to injure corn in other studies (Porterfield and Wilcut 2006). Trifloxysulfuron sodium reduced corn heights more than flazasulfuron both years when rates were less than 10% of the full rate (Figures 1 and 2). In 2009, the trend lines appear similar between flazasulfuron and trifloxysulfuron sodium but the lower half of trend lines is obscured by numerous data points at lower rates (Figure 2). Values of *i* (Equation 2) were approximately 4 times greater for the trend of trifloxysulfuron sodium rates on percentage corn height reduction compared to that obtained with flazasulfuron rates (Figure 2). These differences in *i* value indicate trifloxysulfuron sodium reduces corn height more than flazasulfuron as rate approaches zero.

Drift Prediction

Bioassay trend lines were used to cross reference observed corn height reductions from corn plants exposed to possible herbicide drift to determine the rate of herbicide drift that occurred at various distances down wind of the sprayer. Analysis of variance indicated the year by distance interaction was significant ($P < 0.001$). Regressions were not significant for effects of distance from application on predicted herbicide rate. Therefore, data are presented separately by year and means within years are separated with Fisher's Protected Least Significant Difference (Table 1). The year interaction was probably caused by differences in predicted herbicide rate at the 0 m distance between years (Table 1). In 2008, plants at the 0 m distance were predicted to receive 98 and 68% of the full rates of flazasulfuron and trifloxysulfuron sodium, respectively (Table 1). In 2009, plants at the 0 m distance were predicted to receive no more than 9% of the full rate of either herbicide (Table 1). It was difficult to estimate the exact position of the boom edge and more plants could have been over sprayed in 2008 than in 2009. At distances greater than 0 m, predicted rates were usually less than zero. Negative rate predictions were preserved for ANOVA to maintain variance but means were expressed as "less than zero" in Table 1 to avoid confusion. For flazasulfuron, a positive herbicide rate was predicted only at 4.6 m in 2009 (Table 1). For trifloxysulfuron sodium, positive herbicide rates were predicted at 1.5 m in 2008 and 4.6 m in 2009 (Table 1). Previous drift studies using tractor mounted sprayers indicate a buffer zone of 6-10 m is acceptable for perennial plants with no negative effects beyond 8 m (Marrs et al. 1991a, 1991b). Marrs et al. (1993) conducted drift studies using ragged robin (*Lychnis flos-cuculi*) seedlings and recorded injury 20 m downwind. Compared to perennials, seedling are more sensitive to glyphosate spray drift thus attributing to increased buffer distances.(Marrs et al. 1991a, 1991b; 1997) Spray boom height varied between this study and Marrs et al (1991a, 1991b; 1997) studies, 61 to 80 cm, respectively, which may account for the lower bufferzone predicted for this study. Height of spray applicator is one variable influencing drift distance (Smith et al. 2000). These results indicate a 30 m buffer requirement on the flazasulfuron herbicide label is unnecessary when maximum boom height and spray droplet diameter requirements, utilized in this study, are not exceeded.

SOURCES OF MATERIALS

[1] Potting media, Metro-Mix 220™, Scotts-Sierra Horticultural Products Co., 14111 Scottslawn Road, Marysville, OH 43041.[2] Toro Multipro® 1200, The Toro Company Landscape Contractor Business, 8111 Lyndale Avenue South Bloomington, MN 55420 USA

[3] Flazasulfuron 25 DF™ Herbicide ISK Biosciences Corporation, 2237 Haden Road, Houston, TX 77015-6449, USA.

[4] Monument Herbicide™ Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419, USA.

[5] Kestrel™ 3000 Series, KestrelMeters.com, 2240 Greer Blvd Sylvan Lake, MI 48320 USA

[6] Allen Track Sprayer, Allen Machine Works, 607 East Miller Road, Midland, MI 48640

[7] Chem-Stik Nonionic Spreader-Sticker, Precision Laboratories, Inc., 1429 S. Shields Drive, Waukegan, IL 60085 USA

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Table 1: Predicted rates of herbicide deposited on corn plants spaced various distances downwind of a turf sprayer[a]. Predicted rates are based on comparison of observed percentage growth reduction to hyperbolic trends in growth reduction determined by bioassay (See Figures 1 and 2).

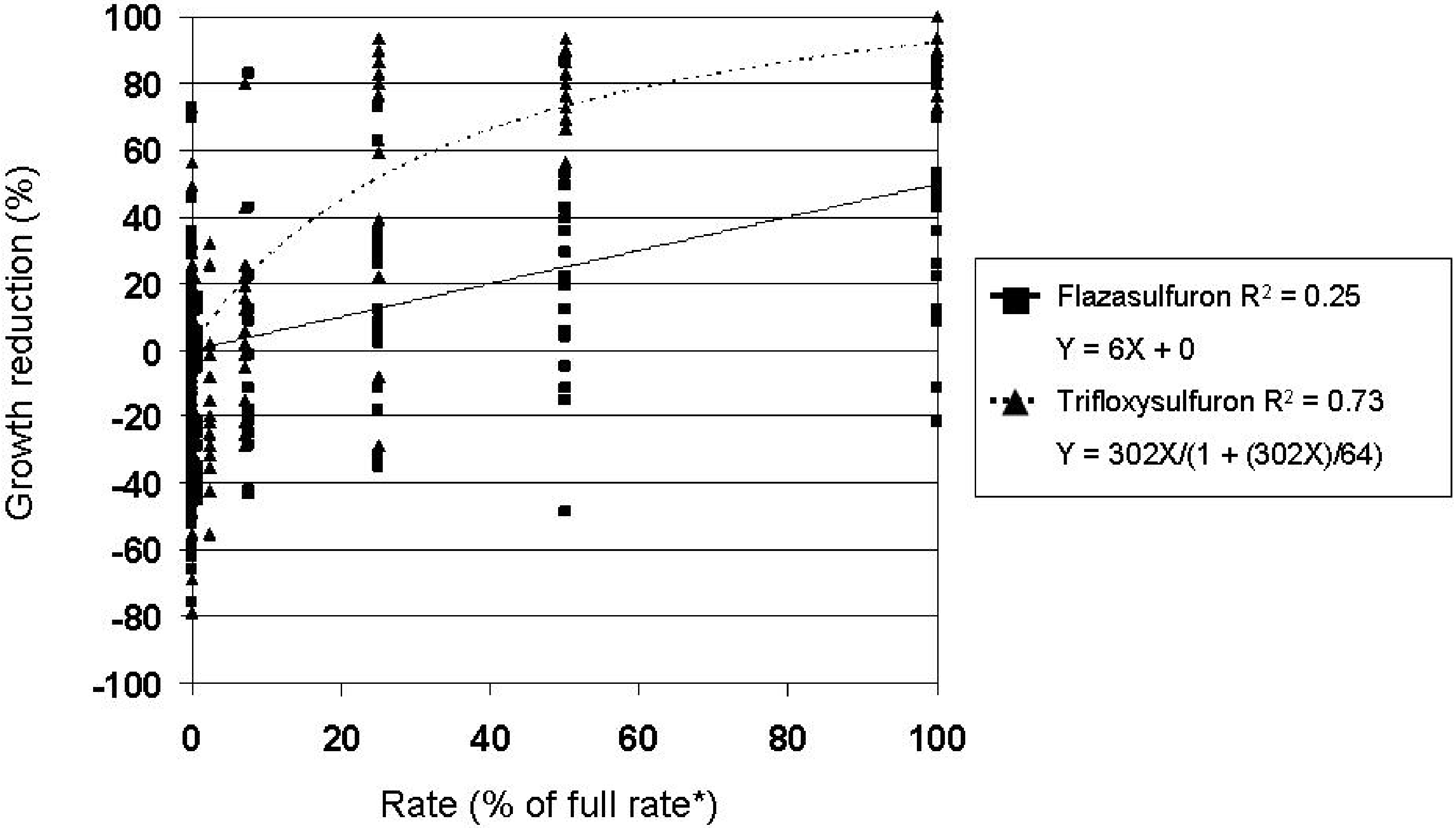
	Flazasulfuron		Trifloxysulfuron sodium	
Distance	2008	2009	2008	2009
	Predicted % of full rate[b]			
0	98.1	3.0	67.7	8.9
1.5	<0	<0	1.5	<0
4.6	<0	0.1	<0	0.2
7.6	<0	<0	<0	<0
15.2	<0	<0	<0	<0
30.5	<0	<0	<0	<0
LSD (0.05)	30.0	1.5	9.9	5.5

[a] A Toro Multipro turf sprayer applied herbicides along a 15 m track perpendicular to wind direction at 4.8 km h^{-1} ground speed and 407 L ha^{-1} application rate. Flazasulfuron was applied with Turbo Tee Jet TTVP 11004 spray nozzles to provide coarse to very coarse spray droplets as specified on the flazasulfuron label. Trifloxysulfuron sodium was applied with Tee Jet XR flat fan 11004 spray nozzles to provide medium to coarse spray droplets as specified on the

trifloxysulfuron sodium label. Wind direction and speeds between 6.4 to 9.6 Km h^{-1} were confirmed with Kestrel wind meters and neutrally buoyant balloons.

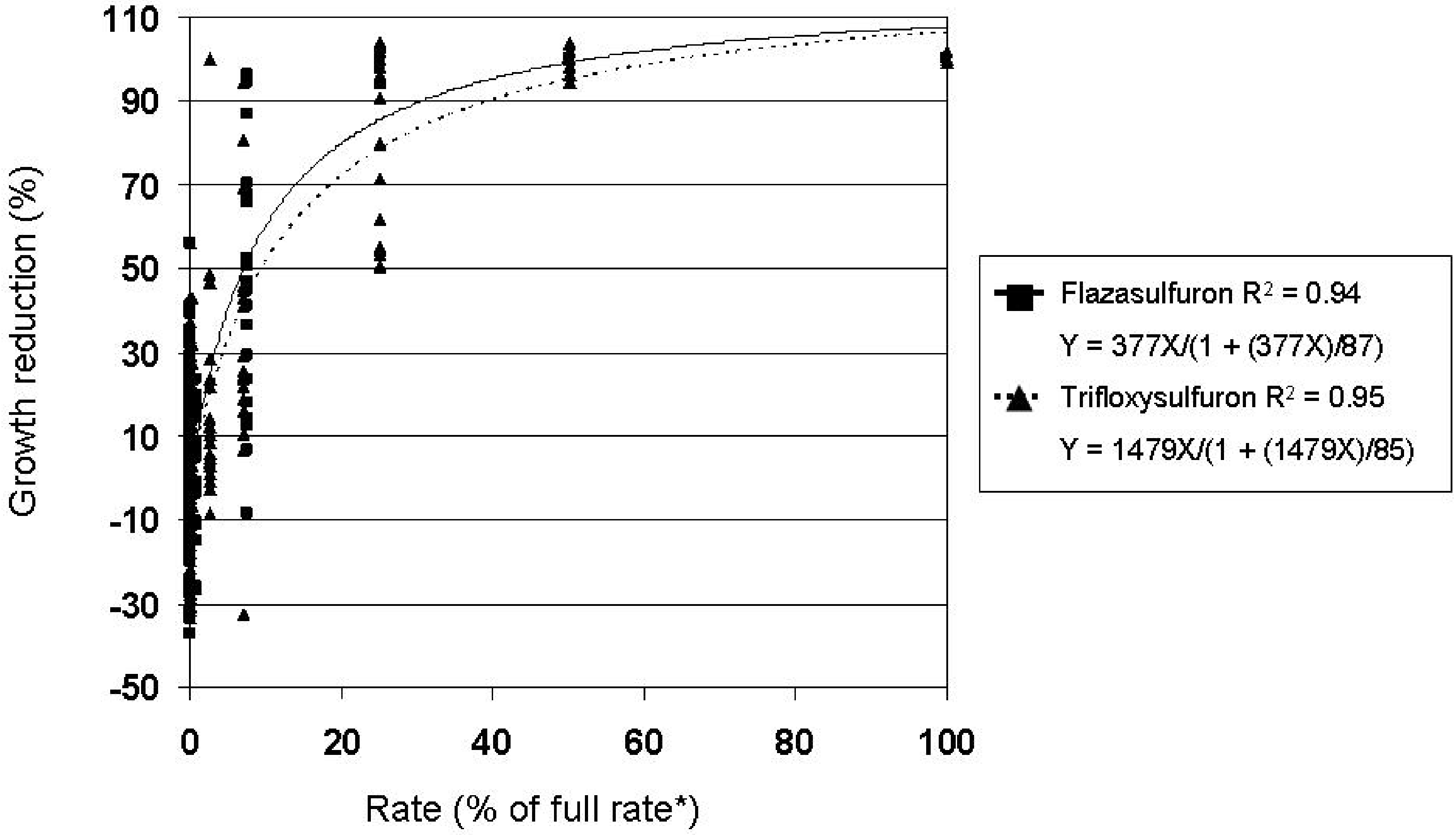
[b] Predicted rates are based on nonlinear regression equations of bioassay plants treated with known rates in a laboratory track sprayer and maintained as cohorts in a green house with plants exposed to potential drift. Predicted rates are expressed as a percentage of the maximum label rates of 52 g ai ha^{-1} for flazasulfuron and 30 g ai ha^{-1} for trifloxysulfuron sodium.

Figure 1. Percent reduction in 3-wk corn growth from flazasulfuron and trifloxysulfuron sodium compared to nontreated corn in 2008. Herbicide rates are expressed as a percentage of normal use rates for flazasulfuron (52 g ai/ha) and trifloxysulfuron sodium (30 g ai/ha).



Growth reduction (%)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
20
40
60
80
100
Rate (% of full rate*)
Flazasulfuron R^2 = 0.25
Y = 6X + 0
Trifloxysulfuron R^2 = 0.73
Y = 302X/(1 + (302X)/64)

Figure 2. Percent reduction in 3-wk corn growth from flazasulfuron and trifloxysulfuron sodium compared to nontreated corn in 2009. Herbicide rates are expressed as a percentage of normal use rates for flazasulfuron (52 g ai/ha) and trifloxysulfuron sodium (30 g ai/ha).


110
90
70
50
30
10
-10
-30
-50
Growth reduction (%)
0
20
40
60
80
100
Rate (% of full rate*)
Flazasulfuron $R^2 = 0.94$
$Y = 377X/(1 + (377X)/87)$
Trifloxysulfuron $R^2 = 0.95$
$Y = 1479X/(1 + (1479X)/85)$