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Nicosulfuron Absorption, Translocation, and Metabolism in Annual Bluegrass and Four Turfgrass Species

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Nicosulfuron provides POST weed control in corn, pastures, and grassy roadsides, and has potential for use in fine turfgrass. The objective of this research was to evaluate tolerance, absorption, translocation, and metabolism of nicosulfuron in annual bluegrass and four turfgrass species. In greenhouse experiments, relative tolerance of grasses to nicosulfuron (35, 70, or 140 g ai ha^{-1}) from high to low was bermudagrass = zoysiagrass > tall fescue > creeping bentgrass > annual bluegrass. In laboratory experiments, grasses had similar foliar and root absorption of ^{14}C-nicosulfuon. Annual bluegrass and creeping bentgrass averaged 80% greater radioactivity per unit dry mass in shoots than bermudagrass following root uptake of ^{14}C-nicosulfuron, but other species were similar to these grasses. At 72 h after treatment (HAT), annual bluegrass metabolized 36% of absorbed ^{14}C-nicosulfuron, which was less than bermudagrass, tall fescue, and zoysiagrass that metabolized 47 to 58%. Creeping bentgrass metabolism of nicosulfuron was similar to annual bluegrass. Tall fescue had similar levels of metabolism to bermudagrass and zoysiagrass, averaging 67%, at 168 HAT but produced fewer metabolites. Overall, turfgrass tolerance to nicosulfuron is associated with relative herbicide concentrations in shoots and differential species metabolism.

Nomenclature: Annual bluegrass (*Poa annua* L.); bermudagrass (*Cynodon dactylon* × *transvaalensis* Burtt-Davy) 'Princess 77'; creeping bentgrass (*Agrostis stolonifera* L.) 'Penn A-4'; tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] 'Titan'; zoysiagrass (*Zoysia japonica* Steud.) 'Zenith'.

Key words: Absorption, efficacy, metabolism, translocation, turf.

Nicosulfuron is an acetolactate synthase ALS inhibitor used for POST weed control in grass crops. Applications from 35 to 70 g ai ha^{-1} effectively control johnsongrass [*Sorghum halepense* (L.) Pers.], Italian ryegrass (*Lolium multiflorum* Lam.), foxtails (*Setaria* spp.), and other problematic weeds in corn (*Zea mays* L.) (Bhowmik et al. 1992; Dobbels and Kapusta 1993; Gubbiga et al. 1996). Recently, nicosulfuron in combination with metsulfuron was registered for pastures and roadsides (Anonymous 2012). This herbicide combination offers practitioners an alternative chemistry for POST grassy weed control in bermudagrass hayfields and roadside turf, with promising potential for use in fine turfgrass (Matocha et al. 2010; Shinn and Thill 2004).

Recently, researchers have evaluated efficacy of nicosulfuron for POST weed control in warm and cool-season turfgrasses. Grichar (2011) noted that sequential nicosulfuron application at 70 g ha^{-1} provided 97% control of bearded sprangletop [*Leptochloa fascicularis* (Lam.) Gray] with no injury to 'Empire' zoysiagrass. It was also reported that nicosulfuron was more effective for controlling bearded sprangletop than several other POST herbicides labeled in turfgrass, including fenoxaprop, flazasulfuron, and MSMA. Beam et al. (2005) noted nicosulfuron at 53 g ha^{-1} controlled Italian ryegrass 69 to 95%, and injured a mixture of Kentucky bluegrass (*Poa pratensis* L.) and tall fescue ≤ 10% at 10 wk after treatment (WAT). The researchers surmised that nicosulfuron could be used for Italian ryegrass control in these cool-season grasses if temporary injury is acceptable.

Nicosulfuron has potential for controlling annual bluegrass in turfgrass. In field experiments, POST applications of nicosulfuron from 35 to 70 g ha^{-1} alone or with rimsulfuron effectively controlled annual bluegrass without injuring bermudagrass (McElroy 2009; personal observation). Currently, there is no sulfonylurea that effectively controls annual bluegrass, johnsongrass, or Italian ryegrass and is safe to both warm and cool-season turfgrasses. Nicosulfuron could have potential for use in lawns with mixed species, such as bermudagrass and tall fescue, or turf that borders species susceptible to other POST herbicides.

Although weed control efficacy of nicosulfuron in turf has been reported, there has been limited research on tolerance levels of various turfgrass species to nicosulfuron. Research is needed to evaluate tolerance of turfgrass species to nicosulfuron and physiological

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basis of selectivity. The objective of this research was to evaluate efficacy, absorption, translocation, and metabolism of ^{14}C-nicosulfuron in annual bluegrass and four turfgrass species.

Materials and Methods

Turfgrass Tolerance. Two greenhouse experiments were conducted at the University of Georgia in Griffin, GA, from July to September 2013. Annual bluegrass, 'Penn A-4' creeping bentgrass, and 'Titan' tall fescue were seeded in a greenhouse set to 25/15 C (day/night), while 'Princess-77' bermudagrass and 'Zenith' zoysiagrass were seeded in a greenhouse set for 32/25 C. Annual bluegrass was established using seed collected from indigenous populations in Griffin. Approximately 10 seed were planted in pots (3.8 cm diameters and 20 cm depths) filled with sand : peat (80 : 20 v/v). Pots were fertilized biweekly during establishment at 24 kg N ha^{-1}. Grasses were irrigated as needed to prevent wilting, allowed to develop three to five tillers before applying treatments and were clipped with shears weekly at a 5-cm height. After establishment, all species were placed together in a greenhouse set for 32/25 C, clipped at 5-cm height, and irrigated to prevent wilting and were acclimated in the greenhouse for 72 h before applying treatments.

A broadcast treatment of nicosulfuron (Accent 75DF, E. I. du Pont de Nemours and Co., 1007 Market St., Wilmington, DE 19898) was applied to grasses at 0, 35, 70, or 140 g ai ha^{-1}. Grasses were not irrigated for 24 HAT, but were then irrigated thereafter to prevent moisture stress. Experimental design was a randomized complete block with four replications. The blocking factor for the experiment was for the potential variability from location in the greenhouse. Treatments were applied with a single nozzle CO_2 pressured sprayer at 374 L ha^{-1}.

Injury was evaluated visually at 2 and 4 WAT on a 0 to 100 scale where 0 equaled no injury and 100 equaled complete desiccation compared to the nontreated. Shoots were harvested at 4 WAT, oven-dried at 60 C for 72 h, and weighed. Shoot dry weight was converted to percent reductions from the nontreated by replication for each species. Data were analyzed in SAS (SAS version 9.3, SAS Institute Inc., Cary, NC 27513) using the General Linear Model Procedure as described by McIntosh (1983). Means were separated with Fisher's Protected LSD test at $\alpha = 0.05$. Experiment by treatment interactions was not detected, and thus, results were pooled over both experiments.

Foliar Absorption and Translocation. Two experiments were conducted in Griffin in May 2013 using a modified methodology from Carey et al. (1997) for evaluating ^{14}C-nicosulfuron absorption. Grasses were established with aforementioned materials and methods. Pots were thinned to one plant after emergence and were allowed to develop three to five tillers before applying treatments. Pots were placed in a growth chamber (Percival Scientific, Inc., 505 Research Drive, Perry, IA 50220) set for 27/20 C (day/night) with 12-h photoperiod of 350 µmol m^{-1} s^{-1} and approximately 50% relative humidity. Plants used in the experiments were selected based on the size and uniformity across species. Plants were watered as needed to prevent wilting, and acclimated in the growth chamber for 3 d before applying treatments.

The two experiments were conducted as completely randomized designs with four replications. A broadcast application of nicosulfuron at 70 g ha^{-1} was made to grasses using a single nozzle CO_2 pressured backpack sprayer calibrated to deliver a spray volume of 374 L ha^{-1}. Immediately following the herbicide application, a fully expanded leaf of each plant was spotted with two 1-µl droplets of ^{14}C-nicosulfuron (55 mCi mmol^{-1}, pyrimidine ring labeled, 98% chemical purity) solution containing a total of 100 Bq of radioactivity using a 10-µl microsyringe (Hamilton Co., Reno, NV 89502). The spotting solution was prepared using formulated nicosulfuron at a concentration 187.165 mg L^{-1} and 0.25% v/v crop oil (Agri-Dex, Crop Oil Concentrate, Helena Co., Collierville, TN 38017). The 187.165 mg L^{-1} concentration is equivalent to the concentration achieved when nicosulfuron is applied at 70 g ha^{-1} at 374 L ha^{-1}. This adjuvant was chosen from pilot experiments to help facilitate deposition of droplets on the leaf surface.

Four plants (roots + shoots) of each species were harvested at 4, 24, and 96 HAT. The treated leaf was excised from the plant and unabsorbed ^{14}C was washed off by swirling the leaf in a 20-ml glass scintillation vial (1654 High Hill Road, Swedesboro, NJ 08085) with 3 ml of 50% acetonitrile solution for 45 s followed by rinsing with additional 2 ml. This methodology was chosen from pilot experiments that provided > 95% ^{14}C recovery within 30 s after herbicide treatments (data not shown). Plant samples were oven dried at 60 C and then combusted for 2 min in a biological oxidizer (Model OX-500, R.J. Harvey Instrument Corp., Hillsdale, NJ 07642). The entire plant of each grass was oxidized at the 4- and 24-h harvest timing to quantify absorption. For grasses harvested at 96 HAT, the treated leaf, nontreated shoots, and roots were oxidized separately for determining ^{14}C distribution. Radioactivity was then quantified with liquid scintillation spectrometry (LSC, Model LS6500, Beckman-Coulter, Inc., Fullerton, CA 92834-3100).

Percent absorption was determined by dividing total radioactivity in samples by the amount applied. Percent ^{14}C distribution was calculated by dividing the radioactivity recovered in the samples by the total radioactivity recovered in each plant. Data were subjected to analysis of variance in SAS, and means were separated using Fisher's Protected LSD test at $\alpha = 0.05$. Experiment by treatment interactions was not detected, and thus, results were pooled over experiments.

Root Absorption and Translocation. Two experiments were conducted in Griffin from April to May 2013 using aforementioned plant materials and greenhouses. Root absorption and translocation of ^{14}C-nicosulfuron in turfgrasses was evaluated using a methodology modified from previous research by Lycan and Hart (2006b). Grasses were removed from the pots after reaching three to five tiller stages and soil was washed from roots. Plants were then grown hydroponically in a 4-L plastic tank filled with half-strength Hoagland solution (Hoagland and Arnon 1950). Roots were suspended in solution by placement through holes in a floating Styrofoam board (12961 San Fernando Road, Sylmar, CA 91342), and aluminum foil covered the sides of the tank to shield roots from light. An aquarium pump (Shkerry Aqua®, Shanghai Uni-Aqua Co., Ltd, Chang Shou Road, Shanghai 200042, China) was used to provide oxygen to the solution.

Plants were acclimated to hydroponic culture for 7 d in the aforementioned growth chamber. The plants were then placed individually into 50-ml plastic tubes filled with 25 ml half-strength Hoagland solution spiked with a total 292 Bq of ^{14}C-nicosulfuron. Formulated nicosulfuron was added to tubes to simulate a 70 g ha^{-1} surface area application rate. Plant roots were submerged in the herbicide solution by placing cotton balls around the base of shoots and tubes were covered with aluminum foil.

Plants were harvested at 72 HAT. Roots were rinsed with 5 ml of 50% acetonitrile solution, and blotted on paper towels. Grasses were then separated to shoots and roots, oven-dried at 60 C, weighed, and combusted for 2 min in a biological oxidizer (Model OX-500, R.J. Harvey Instrument Corp.). Radioactivity in each sample was determined using LSC.

Experiments were conducted in completely randomized designs with four replications. Percent absorption was determined by dividing the radioactivity recovered in the whole plant by the total radioactivity applied. Percent ^{14}C distribution was calculated by dividing radioactivity recovered in the samples by the total radioactivity in the whole plant. Specific radioactivity was calculated by dividing Bq recovered by the sample dry weights. Data were subjected to analysis of variance in SAS, and means were separated using Fisher's Protected LSD test at $\alpha = 0.05$. Experiment by treatment interactions was not detected, and thus, experiments were combined.

Metabolism Experiments. Two experiments were conducted in Griffin in May 2013 using a methodology modified from ^{14}C-nicosulfurom metabolism experiments in grasses by Carey et al. (1997). The five species were established with aforementioned materials and methods. Once grasses reached three to five tiller stages, plants were selected for treatments based on size and uniformity across species and acclimated in the aforementioned growth chamber for 3 d prior to treatments. Experimental design was completely randomized with four replications.

A broadcast treatment of nicosulfuron at 70 g ha^{-1} was applied to grasses with previously mentioned CO_2-pressured sprayer calibrated to deliver 374 L ha^{-1}. Immediately after broadcast applications, two 1-µl droplets of ^{14}C-nicosulfuron containing a total 1.2 kBq were applied to a fully expanded leaf of each plant with a 10-µL microsyringe (Hamilton Co., Reno, NV 89502). The spotting solution contained formulated nicosulfuron to simulate 70 g ha^{-1} at 374 L ha^{-1}, and crop oil concentrate was added at 0.25% v/v to facilitate deposition on the leaf surface.

Treated leaves were harvested at 72 or 168 HAT, as described in foliar absorption experiments, and samples were stored at −20 C. The treated leaf was chosen for sampling to ensure sufficient radioactivity was present for metabolite quantification, and is consistent with previous research on nicosulfuron metabolism in broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], corn, johnsongrass, and other species (Carey et al. 1997; Gallaher et al. 1999; Simpson et al. 1994). Harvest timings were chosen to evaluate degradation of the herbicide over a 1-wk period and to ensure sufficient time had

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Table 1. Injury and dry shoot weight reductions of five grasses at 4 wk after nicosulfuron treatments averaged over experiments, 2013, Griffin, GA.

Nicosulfuron rate	Injury		Shoot dry weight (4 WAT)
	2 WAT[a]	4 WAT	
g ai ha^{-1}	%		% of nontreated
35	14	27	38
70	18	34	35
140	24	51	50
$LSD_{0.05}$	4	5	8
Species[b]			
Annual bluegrass	37	74	63
Bermudagrass	15	20	31
Creeping bentgrass	13	38	46
Tall fescue	15	37	36
Zoysiagrass	14	18	30
$LSD_{0.05}$	5	6	10
Rate	*[c]	*	*
Species	*	*	*
Rate × Species	NS	NS	NS

[a] Abbreviation: WAT, week after treatment.

[b] Cultivars used in experiments were 'Princess-77' bermudagrass, 'Penn A-4' creeping bentgrass, 'Titan' tall fescue, and 'Zenith' zoysiagrass. Annual bluegrass was an indigenous, annual biotype from Griffin.

[c] * and NS represent significant or not significant at the 0.05 probability level, respectively.

elapsed after applications for separation among species. Samples were then placed in 1.5-ml microcentrifuge tubes (Fisher Scientific, Fair Lawn, NJ 07410) and ground with liquid nitrogen. Vials were filled with 1 ml of 80% acetone, agitated using a rotary shaker for 30 s, and placed in a sonication bath (Fisher Scientific, 300 Industry Drive, Pittsburgh, PA 15275) for 2 h. Vials were then centrifuged for 5 min, and the supernatant was transferred to new vials. From residue oxidation, > 85% of the total ^{14}C recovered was extracted from the leaf. This level of extraction is comparable to previously published research on plant metabolism of nicosulfuron in grasses (Carey et al. 1997; Gallaher et al. 1999).

Supernatant was then transferred to new vials (Thermo Scientific, 320 Rolling Ridge Drive, Bellefonte, PA 16823), and evaporated on a heating block set for 60 C in a fume hood. Samples were resuspended in 250 µl of acetonitrile and spotted on 20 × 20 cm thin layer chromatography plates. The plates were developed to 16 cm in a glass chamber using dichloromethane : methanol : ammonium hydroxide (165 : 30 : 5). The plates were air-dried, and metabolites were detected with a radiochromatogram scanner (BioScan System 200 Imaging Scanner, Bioscan, 4590 MacArthur Boulevard NW, Washington, DC 20007) connected to a computer equipped with Laura Chromatography Data Collection and Analysis Software® (LabLogic System, Inc., 1040 E Brandon Blvd, Brandon, FL 33511). The parent herbicide was identified at retention factor (R_f) = 0.3. Metabolites with $R_f < 0.3$ were considered more polar than the parent herbicide, and metabolites with $R_f > 0.3$ were considered less polar than the parent herbicide. Data were analyzed using PROC GLM in SAS (SAS version 9.0, SAS Institute Inc.), and means were separated by using Fisher's Protected LSD test at $\alpha = 0.05$. Experiment by treatment interactions was not detected, and thus, data were pooled over experiments.

Results and Discussion

Turfgrass Tolerance. Species by rate interactions were not detected for injury or shoot mass reductions, and thus, results are presented by main effects (Table 1). Injury of grasses increased with nicosulfuron rates, ranging from 14 to 24% and 27 to 51% at 2 and 4 WAT, respectively. At 2 WAT, annual bluegrass was injured 37% by nicosulfuron, while other species averaged 14% injury. However, injury increased to 38% in creeping bentgrass and tall fescue at 4 WAT, and was twofold greater than bermudagrass and zoysiagrass.

At 4 WAT, 35 and 70 g ha^{-1} rates of nicosulfuron caused 35% and 38% reduction in shoot mass compared to untreated (Table 1). The differences between the two rates were not significant. Nicosulfuron at 140 g ha^{-1} reduced shoot mass of grasses by 50% from the nontreated, which was greater than lower rates evaluated. Among the grasses evaluated, annual bluegrass had the greatest, 63%, reduction in the shoot mass. Creeping bentgrass shoot mass was reduced 46% by nicosulfuron, which was greater than bermudagrass, tall fescue, and zoysiagrass that averaged 32% reductions.

Bermudagrass and zoysiagrass appeared tolerant to labeled rates of nicosulfuron (35 to 70 g ha^{-1}) in corn, pastures, and hayfields. Similar tolerance levels of these species have been previously reported (Grichar 2011; McElroy 2009), but injury of cool-season turfgrasses has received limited attention. Tall fescue had intermediate tolerance to nicosulfuron over the 4-wk period, and was less susceptible to shoot mass reduction than creeping bentgrass. In previous work, Beam et al. (2005) noted spring applications of nicosulfuron at 39 and 53 g ha^{-1} injured a mixture of Kentucky bluegrass and tall fescue turf by 13 to 31% at 5 WAT. The

Table 2. Distribution of radioactivity at 96 h after foliar applications of ^{14}C-nicosulfuron to five grasses averaged over two experiments, 2013, Griffin, GA.

	^{14}C Distribution		
Species[a]	Treated leaf	Nontreated shoots	Roots
	% of absorbed per plant		
Annual bluegrass	46	44	10
Bermudagrass	51	46	3
Creeping bentgrass	58	34	8
Tall fescue	62	30	8
Zoysiagrass	67	26	7
$LSD_{0.05}$	21	17	4

[a] Cultivars used in experiments were 'Princess-77' bermudagrass, 'Penn A-4' creeping bentgrass, 'Titan' tall fescue, and 'Zenith' zoysiagrass. Annual bluegrass was an indigenous, annual biotype from Griffin.

researchers also reported sequential applications of nicosulfuron at 13 or 27 g ha^{-1} caused 16 to 34% injury at 5 WAT, but turf had < 20% injury after 10 wk. These levels of tall fescue injury may be objectionable for intensively managed areas, but temporary injury may be acceptable when controlling problem weeds, such as annual bluegrass or Italian ryegrass.

Creeping bentgrass was the most susceptible turfgrass species to growth inhibition from nicosulfuron, but had better tolerance than annual bluegrass. Previous research has determined creeping bentgrass tolerance to ALS inhibitors is affected by application timing. For example, Lycan and Hart (2006a) determined that creeping bentgrass had better tolerance to bispyribac-sodium in spring than fall. In growth chamber experiments, creeping bentgrass injury from sulfosulfuron was exacerbated by reductions in temperature from 25 to 15 C (McCullough and Hart 2008). Creeping bentgrass tolerance to ALS inhibitors and other POST herbicides may also depend on cultural practices such as fertility and mowing height (Johnson 1990). Perhaps, sequential applications of low nicosulfuron rates could control annual bluegrass in creeping bentgrass, and therefore warrants further study.

Annual bluegrass was the most sensitive species, and nicosulfuron may have potential for its selective control in turfgrasses. McElroy (2009) noted nicosulfuron mixtures with rimsulfuron effectively controlled annual bluegrass in Tennessee. Other ALS inhibitors have potential for controlling annual bluegrass in cool-season grasses, including bispyribac-sodium and primisulfuron (Hart and McCullough 2007; Lycan and Hart 2006a). However, most ALS inhibitors have specific application regimens required to control annual bluegrass and minimize injury to the cool-season turfgrasses. Further research is warranted to evaluate nicosulfuron rates and regimens in cool-season grasses to optimize efficacy for POST annual bluegrass control.

Absorption and Distribution. Foliar absorption of nicosulfuron was similar across species at all harvests, and averaged 40% (± 4), 57% (± 5), and 65% (± 5) of the applied at 4, 24, and 96 HAT, respectively (data not shown). Turfgrass foliar absorption levels of nicosulfuron are comparable to those previously reported in corn and other plant species. Simpson et al. (1994) noted 30 to 40% of applied ^{14}C-nicosulfuron was absorbed at 4 HAT in corn. Gallaher et al. (1999) noted corn absorbed < 40% of the applied ^{14}C-nicosulfuron at 20/10 C after 4 h, but foliar uptake increased to ≥ 50% of the applied at 30/20 C. Differences among turfgrass species were not detected for foliar uptake of ^{14}C-nicosulfuron, and results were similar to previous work on species with differential tolerance levels. For example, Manley et al. (1999) reported that foliar absorption of ^{14}C-nicosulfuron was similar in resistant and susceptible biotypes of smooth pigweed (*Amaranthus hybridus* L.). Foliar absorption of ^{14}C-nicosulfuron was also similar in experiments in five species with differing tolerance levels to applications (Mekki and Leroux 1995). Similar foliar uptake among tolerant and susceptible species has been reported with other ALS inhibitors including procarbazone, halosulfuron, imazamox, and trifloxysulfuron (Fandrich et al. 2001; McElroy et al. 2004; Pester et al. 2001).

At 96 HAT, annual bluegrass and creeping bentgrass distributed ≈ 20% more foliar-absorbed radioactivity to nontreated shoots than zoysiagrass, but differences were not detected among other species for ^{14}C distribution (Table 2). Bermudagrass distributed 4 to 7% less ^{14}C to roots than other species, but distribution was similar for other grasses. Distribution patterns of foliar absorbed radioactivity do not appear to be correlated with species tolerances at 96 HAT.

Differences in uptake, translocation, and total specific radioactivity (Bq g^{-1}) were not detected among the species at 72 h after root absorption of ^{14}C-nicosulfuron. Grasses averaged 11% (± 1) absorption of root-applied ^{14}C-nicosulfuron, and distributed 50% (± 2) of the absorbed ^{14}C to the shoots (data not shown). Total specific radioactivity from the root absorbed ^{14}C-nicosulfuron was similar

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Table 3. Specific radioactivity at 72 h after root-applied ^{14}C-nicosulfuron to five grasses averaged over two experiments, 2013, Griffin, GA.

Species[a]	Specific radioactivity		
	Roots	Shoots	Total[b]
	Bq g^{-1}		
Annual bluegrass	354	234	159
Bermudagrass	389	138	127
Creeping bentgrass	453	262	158
Tall fescue	502	196	150
Zoysiagrass	689	196	161
$LSD_{0.05}$	293	90	NS[c]

[a] Cultivars used in experiments were 'Princess-77' bermudagrass, 'Penn A-4' creeping bentgrass, 'Titan' tall fescue, and 'Zenith' zoysiagrass. Annual bluegrass was an indigenous, annual biotype from Griffin.

[b] Total specific radioactivity was calculated by dividing sum of radioactivity in roots and shoots by the total mass of roots plus shoots biomass.

[c] Abbreviation: NS, not significant.

Table 4. Metabolism of ^{14}C-nicosulfuron in five grasses in two combined experiments, 2013, Griffin, GA.

Species[a]	Parent herbicide recovery	
	72 HAT[b]	168 HAT
	% of total ^{14}C extracted	
Annual bluegrass	64	37
Bermudagrass	53	41
Creeping bentgrass	55	30
Tall fescue	42	35
Zoysiagrass	45	24
$LSD_{0.05}$	10	9

[a] Cultivars used in experiments were 'Princess-77' bermudagrass, 'Penn A-4' creeping bentgrass, 'Titan' tall fescue, and 'Zenith' zoysiagrass. Annual bluegrass was an indigenous, annual biotype from Griffin.

[b] Abbreviation: HAT, hours after treatment.

among the grasses at 72 HAT (Table 3). However, annual bluegrass and creeping bentgrass had 90 and 70% greater specific radioactivity in the shoots than bermudagrass, respectively. Specific radioactivity in zoysiagrass roots was 95 and 77% higher than annual bluegrass and bermudagrass, respectively. Differences in specific radioactivity in roots and shoots were not detected among other species.

Differential root uptake and distribution of ALS inhibitors have been reported in grasses. Lycan and Hart (2006b) reported annual and roughstalk bluegrass (*Poa trivialis* L.) distributed ≈ 80% of root-absorbed ^{14}C-bispyribac-sodium to shoots at 72 HAT. It was also noted that creeping bentgrass and Kentucky bluegrass distributed only 66% of root-absorbed ^{14}C to shoots, and could be associated with differential tolerances. Results from the present study suggest absorption and distribution from foliar and root applied nicosulfuron are not attributed to selectivity or differential tolerance levels among turfgrass species. However, greater concentrations of nicosulfuron or derivatives in shoots may contribute to greater injury in the susceptible species, such as annual bluegrass and creeping bentgrass, compared to grasses with less injury or growth inhibition potential.

Metabolism. Two major metabolites of nicosulfuron were identified in all the species at 72 HAT at R_f 0.06 and 1.0. Similar metabolite formations were reported by Carey et al. (1997) at 72 HAT of ^{14}C-nicosulfuron in corn, giant foxtail (*Setaria faberi* Herrm.), and johnsongrass. At 168 HAT, annual bluegrass and zoysiagrass had a metabolite at R_f 0.21 that was not detected in other species. Additionally, a metabolite at R_f 0.9 was developed in bermudagrass, creeping bentgrass, and zoysiagrass that was not detected in annual bluegrass or tall fescue at 168 HAT.

Annual bluegrass metabolized 36% of ^{14}C-nicosulfuron at 72 HAT, but was similar to creeping bentgrass (Table 4). However, annual bluegrass metabolism was 10 to 20% less than all other species. Tall fescue metabolism of nicosulfuron was comparable to zoysiagrass at 72 HAT, which both species had more metabolism than bermudagrass. At 168 HAT, zoysiagrass metabolized 76% of nicosulfuron, and was 15% greater than annual bluegrass, bermudagrass, and tall fescue. Parent herbicide levels in annual bluegrass measured at 168 HAT were 37% of total ^{14}C, similar to that calculated for all grasses except zoysiagrass.

Turfgrass metabolism of nicosulfuron may be critical for detoxification by tolerant species, and is similar to reports on nicosulfuron selectivity in corn and other grasses. Carey et al. (1997) reported susceptibility of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and johnsongrass to nicosulfuron resulted from less metabolism than in corn, a tolerant species. Hinz and Owen (1996) noted that nicosulfuron metabolism in corn was > 18 times faster than wooly cupgrass [*Eriochloa villosa* (Thunb.) Kunth], a sensitive species. Similar metabolism of nicosulfuron in corn was reported by Christopher et al. (1992) over a 48-h period. In other experiments, broadleaf signalgrass susceptibility to nicosulfuron was associated with slower metabolism at 4 HAT than primisulfuron, a less phytotoxic herbicide (Gallaher et al. 1999). Collectively, it was surmised that the nicosulfuron selectivity for grassy weed control in corn results from differential species metabolism.

Selectivity of other ALS inhibitors has also been attributed to metabolism. Koeppea et al. (2000) determined that corn rapidly metabolized ^{14}C-rimsulfuron after 1 h, while johnsongrass and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] did not reach comparable levels until 38 and 27 h, respectively. In turfgrasses, Baird et al. (1989) reported that centipedegrass [*Eremochloa ophiuroides* (Munro) Hack.] metabolized twice as much ^{14}C-sulfometuron than bahiagrass (*Paspalum notatum* Fluegge) at 72 HAT. Park et al. (2004) observed that 80% of the absorbed ^{14}C-propoxycarbazone was metabolized in susceptible and resistant biotypes of downy brome (*Bromus tectorum* L.), but resistant biotypes had more rapid metabolism. Similar differences in metabolism have been noted in tolerant and susceptible species for other ALS inhibitors including chlorsulfuron, procarbazone, primsulfuron, sulfosulfuron, and trifloxysulfuron (Fandrich et al. 2001; Hoseeini et al. 2011; Mekki and Leroux 1995; Richardson et al. 2003).

Overall, annual bluegrass was more susceptible to nicosulfuron injury than the two cool and warm-season turfgrasses evaluated in the present study. Creeping bentgrass was the most sensitive turfgrass species to nicosulfuron, and tall fescue was more injured than the warm-season grasses. Although responses of bermudagrass forage varieties have been evaluated, bermudagrass turf appeared tolerant to nicosulfuron and was comparable to zoysiagrass. Nicosulfuron had an acropetal movement in the plants. The relative concentration in shoots appeared to be associated with higher phytotoxicity in susceptible turfgrass species. Grass species with higher injury from nicosulfuron also had lower metabolism or fewer metabolites compared to the species with higher tolerances. The physiological basis for nicosulfuron selectivity in turfgrasses seems to be associated with relative herbicide concentrations in the shoots and differential metabolism between the grass species.

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