ABSTRACT

GANNON, TRAVIS WILLIAM. Leaching Potential and Efficacy of Select Herbicides in Turfgrass Environments. (Under the direction of Dr. Fred Yelverton.)

Pesticide regulations based on environmental fate data collected from other agricultural systems may be inappropriate for an established turfgrass system. Field lysimetry experiments were conducted during 2007 – 2009 to compare downward mobility of select herbicides in an established bermudagrass fairway and bare ground systems. Summer and winter applications were also compared. Evaluated herbicides included atrazine, mesotrione, monosodium methylarsonate, pendimethalin and sulfentrazone. Lysimeters were removed 60 or 120 d after initial treatment and analyzed for parent analyte or total arsenic (monosodium methylarsonate) content. Herbicides generally remained in vegetation or surface soil of a bermudagrass system whereas they distributed beyond the surface soil of a bare ground system. Herbicides likely remained in surface soil or vegetation of bermudagrass due to increased organic matter content. Additionally, greater herbicide concentrations were reported after winter applications, likely due to decreased biotic and abiotic degradation. These data confirm herbicide downward mobility varies among turfgrass and bare ground systems and may allow regulatory agencies to view pesticide fate among these systems independently. These data may also assist managers in devising comprehensive integrated pest management principles that may reduce adverse environmental effects.

Another series of experiments were conducted to determine the efficacy of select herbicides on common and troublesome perennial sedge species. Field experiments were conducted during 2007 and 2008 to evaluate herbicide treatment regimes for postemergent purple nutsedge and false-green kyllinga control. Sedge control varied among years likely

due to reduced rainfall during 2007. During 2007, pooled across herbicide rate and number of applications, sulfosulfuron provided greater purple nutsedge control than trifloxysulfuron. Sulfosulfuron and trifloxysulfuron provided similar purple nutsedge control in 2008, although each were less effective compared to 2007. During 2007, sulfosulfuron and trifloxysulfuron provided excellent false-green kyllinga control, while trifloxysulfuron provided greater control compared to sulfosulfuron in 2008. Regardless of year, sulfentrazone provided < 30 and 60% purple nutsedge and false-green kyllinga control, respectively. Data from this research also indicates a sequential application enhances sedge control compared to a single application. Further, a sequential application 6 WAIT provided that greatest sedge control with evaluated herbicides. These data indicate sulfosulfuron or trifloxysulfuron may offer acceptable postemergent perennial sedge control in tolerant warm-season turfgrasses; however, sulfentrazone alone or tank-mixed with select herbicides did not provide acceptable sedge control. Greenhouse experiments were conducted to determine the effect of selective herbicide placement on false-green kyllinga, purple nutsedge, and yellow nutsedge shoot number, shoot weight and root weight. Selective herbicide placement levels included soil only, foliage only, and soil + foliage while evaluated herbicides included sulfentrazone, sulfosulfuron and trifloxysulfuron. Yellow nutsedge and false-green kyllinga were more sensitive to sulfentrazone, compared to purple nutsedge. Purple nutsedge and false-green kyllinga were more sensitive than yellow nutsedge to sulfosulfuron, while evaluated species responded similarly to trifloxysulfuron. Soil-only and soil + foliage-applications provided the highest level of growth suppression, indicating herbicide-soil contact is required for optimum sedge control with evaluated herbicides.

Leaching Potential and Efficacy of Select Herbicides in Turfgrass Environments

by
Travis William Gannon

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Crop Science

Raleigh, North Carolina

2011

APPROVED BY:

Dr. Rex A. Liebl	Dr. Lane P. Tredway
Dr. Fred H. Yelverton Chair of Advisory Committee	Dr. Jerome B. Weber

DEDICATION

This dissertation is dedicated to the memory of my sister, Allison Lea Gannon, and in honor of my daughter, wife, mother and father.

Without each of their love and support, none of my accomplishments thus far would be possible.

BIOGRAPHY

Travis William Gannon was born and raised in Julian, a small community south of Greensboro, NC to David and Cecelia Gannon. After graduating from Southeast Guilford High School, Travis received a Bachelor of Science degree with honors from North Carolina State University in Technical Agronomy with a concentration in turfgrass management. After completing his B.S. degree in 1999, Travis married Daniele Neese Gannon and began working as a Research Technician in the Crop Science Department at North Carolina State University while simultaneously pursuing a Master of Science degree. Travis completed his M.S. thesis entitled 'Establishment and Allelopathic Potential of Centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.) In Utility Turf Areas' in May 2003 under the direction of Dr. Fred Yelverton. After completing his M.S. degree, Travis continued working in the Crop Science Department and welcomed the birth of his daughter, Cameron Lea Gannon before pursuing a PhD in 2006.

While at NCSU, Travis received several awards and honors including: Carolinas Golf Course Superintendents Association scholarship, United States Golf Association Green Section Intern, Southern Weed Science Society annual meeting oral presentation contest second place, NC Crop Protection School oral presentation contest winner and was inducted into Golden Key and Gamma Sigma Delta National Honor Societies. Travis currently lives in Apex, NC and enjoys spending time outdoors with his family.

ACKNOWLEDGMENTS

There are a number of individuals I would like to recognize for their contribution to my development and success. First, I would like to thank Dr. Fred Yelverton for direction and guidance throughout my graduate career. My sincere gratitude for the professional guidance you have provided can't be put into words. I would also like to thank Dr. Rex Liebl for your guidance and assistance with sample analysis. I would also like to thank Dr. Jerry Weber for your willingness to help with field lysimeters and manuscript review. Finally, I would like to thank Dr. Lane Tredway for your support and manuscript review.

I would also like to thank and extend gratitude to my wife and best friend, Daniele Neese Gannon. Without your unconditional love, support and kindness, I would not have accomplished many things including this degree. Next, I would also like to extend my gratitude to my six-year old daughter, Cameron Lea Gannon. I apologize for the time I have been away and for any instance where you did not have my undivided attention. I would also like to thank my parents, David and Cecelia Gannon for the unconditional love and support they have lent. None of my success would be possible without the core values you instilled in me at a young age. I would also like to thank Mitch Clendenin and Danny Neese, among others, who have helped me in various ways, but mainly for the friendship.

I would also like to acknowledge the friendship of other graduate students and NCSU personnel who made my graduate career at NCSU enjoyable. Finally, I would like to reiterate and thank my wife and daughter for their unwavering support, understanding, faith, patience and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

SELECTIVE EXPOSURE OF YELLOW NUTSEDGE (*CYPERUS ESCULENTUS*), PURPLE NUTSEDGE (*CYPERUS ROTUNDUS*) AND FALSE-GREEN KYLLINGA (*KYLLINGA GRACILLIMA*) TO POSTEMERGENCE HERBICIDES

LIST OF FIGURES

INTRODUCTION AND LITERATURE REVIEW

Downward herbicide mobility. Pesticides are viable management tools in many facets of agriculture but must be managed carefully to prevent environmental contamination. In 2001, greater than 460 million kg pesticides were used in the U. S. (United States) (Kiely et al. 2004). Downward pesticide mobility is an important component of environmental fate. Pesticides have been detected in shallow groundwater in the U. S. in recent years although 95% of reported concentrations were low (Barbash et al. 2001; Kolpin et al. 1998).

When a pesticide is applied, various processes ensue which may include photodegradation, volatilization, plant absorption, soil adsorption, microbial or chemical degradation, or leaching (Cummings 2004; Gardner et al. 2000; Horst et al. 1996; Hurto et al. 1979; Weber 1991). Previous research suggests pesticide behavior and dissipation may vary among established turfgrass and other systems for various reasons including larger, more diverse soil microbial populations and increased organic matter (OM) content in established turfgrass systems (Gardner et al. 2000; Gold et al. 1988; Horst et al. 1996; Hurto et al. 1979; Magri and Haith 2009; Shi et al. 2006; Smith and Paul 1988).

Clay and OM are considered active fractions for pesticide sorption. Although OM generally accounts for a small portion of soil by volume, it has the most profound effect on pesticide adsorption (Alexander 2000; Farenhorst 2006; Hatzinger and Alexander 1997; Nam et al. 1998; Wauchope et al. 2002; Weber et al. 1993). Adsorption of pesticides to colloidal surfaces reduces leaching potential (Weber et al. 1993). With ionizable pesticides, soil pH also affects speciation between molecular and dissociated species (Corbin et al. 1971). With acidic pesticides, as pH becomes greater than pK_a, dissociated (deprotonated, anionic) species will dominate while as pH becomes less than pK_a, molecular (neutral) species will dominate. With basic pesticides, as pH becomes greater than pK_a, molecular species will dominate while protonated (cationic) species will dominate as pH becomes less than pK_a. When pH is near pK_a, the pesticide will exist as a mixture of dissociated and molecular species. Soil pH also affects protonation of OM functional groups. Protonation of specific functional groups affects the sorptive capacity as charged functional groups are able to bind more pesticides possessing the opposite charge. Clay surfaces may possess a net negative charge due to isomorphic substitution and may readily bind cations while anions are generally repelled and more mobile (McBride 1994). Nonionic pesticides may desorb readily with water, suggesting that weak physical attractive forces are involved and their adsorption is inversely related to aqueous solubility (Carringer et al. 1975).

Although arsenic (As) is considered immobile in most soils, U.S. EPA has enacted a phase-out for all organic arsenical pesticides including MSMA in turfgrass systems. Currently, the phase-out calls for no organic arsenical pesticide use after 2013 in turfgrass systems while use in cotton is eligible for reregistration (U.S. EPA 2010). The organic arsenical phase-out is currently in deliberation and was based on the limited value and adequate alternatives as well as the conversion of organic arsenical pesticides to more toxic species (Hughes 2002; Yelverton, personal communication). Some previous research included experimental sites that were previously used for agriculture production and had been treated with As-based pesticides resulting in elevated As concentrations (Bednar et al. 2002). Additionally, some of the work was completed on a landfill which may have possessed elevated As concentrations (Khan et al. 2004).

Managed turfgrass areas include residential and commercial lawns, roadsides, golf courses, sports fields, airports, and other utility turfs (Beard and Green 1994; Turgeon 2008). Managed turfgrass in the U.S. comprises 16 to 20 million hectares (ha) or approximately 15% of total cropland (Milesi et al. 2005; Qian and Follett 2002) and three times greater than any irrigated crop in the U.S. (Milesi et al. 2005). Expectations vary for turfgrass areas based on many factors leading to different management intensities (Turgeon 2008). Pesticides are commonly applied to managed turfgrass systems to attain desirable aesthetic value, turfgrass quality or function. Pesticide applications have been reported to be up to eight and three times greater annually on golf courses and residential turf, respectively, compared to agricultural land (Koppell 1994; Schueler 2000). The public may perceive turf areas unsafe because of increased pesticide use (Balogh and Anderson 1992; Gruen 2007; Kenna 1995).

Inherent differences exist among turfgrass and row crop agriculture with respect to pesticide fate. In established turfgrass environments, pesticides are not applied directly to soil, thereby reducing the fraction of pesticide that may leach. Gasper et al. (1994) reported 54% of applied pendimethalin was retained on turfgrass foliage immediately after application compared to a preemergent application in row crops where 100% may reach the soil immediately. Also, if one compares a preemergence (PRE) application in a row crop and a turfgrass environment, pesticides may be readily absorbed by plants in an established turfgrass environment whereas in a row crop, there are no plants present at application to absorb pesticides. Established turfgrass systems are not tilled and during periods of active growth, the turf is mowed and grass clippings are typically returned into the turf canopy. As grass clippings and other plant material decompose, OM accumulates near the soil surface indicating soils of turfgrass systems generally have higher levels of soil OM that increase with age (Bandaranayake et al. 2003; Hixson 2008; Qian and Follett 2002; Shi et al. 2006). Higher levels of OM may increase pesticide adsorption and reduce plant uptake or leaching (Novak et al. 1997; Weber et al. 1993). Further, established turfgrass systems support larger, more diverse microbial populations which affect pesticide fate (Magri and Haith 2009).

Assuming differences in OM content and microbial populations, one may assume pesticide fate would differ among turfgrass and a bare ground system, and this has been previously confirmed (Gardner et al. 2000). Gardner and Branham (2001) concluded that ethofumesate downward mobility was reduced by $\geq$ 95% in turfgrass systems compared to bare ground. Similarly, Cummings (2004) reported that fipronil, imazaquin, prodiamine, pronamide and simazine tended to distribute uniformly through 15 cm of fallow soil whereas they remained in the surface soil of a bermudagrass system. Gardner and Branham (2001) also reported ethofumesate half-life in a turfgrass system was three days compared to 51 days in bare ground. Additional evidence confirming pesticide fate varies among systems may allow regulatory agencies to make more precise decisions pertaining to pesticide regulations.

Purple nutsedge and false-green kyllinga control. Purple nutsedge (*Cyperus rotundus* L.) and false-green kyllinga (*Kyllinga gracillima* Miq.) are common perennial sedge species (Cyperaceae) in turfgrass systems that thrive in moist soil conditions (Bendixen and Nandihalli 1987; McElroy et al. 2005). Purple nutsedge and most kyllinga spp. are C_4 plants (Bryson and Carter 2008; Lin et al. 1993) which possess specialized leaf anatomy allowing increased growth and efficiency under high light and temperature regimes (Hattersley 1983;

Lin et al. 1993; Teeri and Stowe 1976). Purple nutsedge and false-green kyllinga also tolerate routine mowing (Summerlin et al. 2000).

Herbicide programs have traditionally included postemergent monosodium salt of methylarsonic acid (MSMA) applications to control summer annual grasses, including crabgrass (*Digitaria* spp.) and goosegrass (*Eleusine indica*), and also controlled nutsedge and kyllinga species. Today, managers rely less on postemergent herbicides in favor of preemergent herbicides that do not control *Kyllinga* and *Cyperus* species from perennial structures thereby leading to increased sedge incidence in turfgrass environments. Selective herbicide options are available in most turfgrasses, although each species is difficult to control long-term as they possess vegetative structures capable of overwintering in select climates including the southeastern United States. Further, data is limited evaluating recently-registered herbicides for selective sedge control in turfgrass systems.

Selective exposure of sedge species to postemergence herbicides. Herbicide efficacy may be governed by herbicide placement and site of uptake and action. Effects of selective herbicide placement on sedge control have been previously reported (McElroy et al. 2003; McElroy et al. 2004; Nandihalli and Bendixen 1988; Reddy and Bendixen 1998; Vencill et al. 1995; Wehtje et al. 1997).

Yellow nutsedge (*Cyperus esculentus* L.) is also a common perennial sedge species in turfgrass systems (Bendixen and Nandihalli 1987; Bryson et al. 1997; McCarty et al. 2008; McElroy et al. 2005). Unlike purple nutsedge and false-green kyllinga, yellow nutsedge is not generally observed in mowing heights typical of a golf course fairway and is more commonly observed in higher mowing heights and nonmown areas (Summerlin 1997, 2000).

Yellow nutsedge has been described as one of the world's worst weeds and is more widely distributed than purple nutsedge (Martínez-Ochoa et al. 2004; McCarty et al. 2008; Stoller and Sweet 1987). Each species exhibits prolific vegetative growth and produce rhizomes while purple and yellow nutsedge also produce basal bulbs and tubers (McCarty et al. 2008; Stoller and Sweet 1987). Information regarding the response of sedge species to currently available herbicides is limited.

Turfgrass is a large commodity in the United States and it is imperative we understand pesticide environmental fate, weed biology and control options to assist managers in the development of comprehensive integrated pest management plans that reduce adverse environmental effects.

LITERATURE CITED

Alexander, M. 2000. Aging, bioavailability, and overestimation of risk from environmental contaminants. Environ. Sci. Technol. 34:4259–4265.

Balogh, J. C. and J. L. Anderson. 1992. Environmental impacts of turfgrass pesticides. *In* J.C. Balogh and W.J. Walker (ed.) Golf course management and construction: Environmental issues. Lewis Publ., Boca Raton, FL.

Bandaranayake, W., Y. L. Qian, W. J. Parton, D. S. Ojima, and R. F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agron. J. 95:558-563.

Barbash, D. E., G. P. Thelin, D. W. Kolpin, and R. J. Gilliom. 2001. Major herbicides in ground water: results from the National Water-Quality Assessment. J. Environ. Qual. 30:831-845.

Beard, J. B. and R. L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 23:452-460.

Bednar, A. J., J. R. Garbarino, J. F. Ranville, and T. R. Wildeman. 2002. Presence of organoarsenicals used in cotton production in agricultural water and soil of the southern United States. J. Agric. Food Chem. 50:7340-7344.

Bendixen, L. E., and U. B. Nandihalli. 1987. Worldwide distribution of purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:61-65.

Bryson C. T. and R. Carter. 2008. *The significance of Cyperaceae as weeds*. In: Sedges: Uses, Diversity, and Systematics of the Cyperaceae (eds. R.F.C. Naczi and B. A. Ford), pp. 15–101. Monographs in Systematic Botany from the Missouri Botanical Garden, St. Louis, Missouri.

Bryson, C. T., R. Carter, L. B. McCarty, and F. H. Yelverton. 1997. *Kyllinga*, a genus of neglected weeds in the continental United States. Weed Technol. 11:838-842.

Carringer, R. D., J. B. Weber, and T. J. Monaco. 1975. Adsorption-desorption of selected pesticides by organic matter and montmorillonite. J. Agric. Food Chem. 23:568-572.Corbin, R. T., R. P. Upchurch, and F. L. Selman. 1971. Influence of pH on the phytotoxicity of herbicides in the soil. Weed Sci. 19:233–239.

Corbin, R. T., R. P. Upchurch, and F. L. Selman. 1971. Influence of pH on the phytotoxicity of herbicides in the soil. Weed Sci. 19:233–239.

Cummings, H. D. 2004. Pesticide downward movement in a bermudagrass system compared with movement in a fallow system. Ph.D dissertation. Raleigh, NC: North Carolina State University. 208 p.

Farenhorst, A. 2006. Importance of Soil Organic Matter Fractions in Soil-Landscape and Regional Assessments of Pesticide Sorption and Leaching in Soil. Soil Sci. Am. J. 70:1005-1012.

Gardner, D. S., and D. E. Branham. 2001. Mobility and dissipation of ethofumesate and halofenozide in turfgrass and bare soil. J. Agric. Food Chem. 49:2894-2898.

Gardner, D. S., B. E. Branham, and D. W. Lickfeldt. 2000. Effect of turfgrass on soil mobility and dissipation of cyproconazole. Crop Sci. 40:1333–1339.

Gasper, J. J., J. R. Street, S. K. Harrison, and W. E. Pound. 1994. Pendimethalin efficacy and dissipation in turfgrass as influenced by rainfall incorporation. Weed Sci. 42:586-592.

Gold, A. J., T. G. Morton, W. M. Sullivan, and J. McClory. 1988. Leaching of 2,4-D and dicamba from home lawns. Water, Air, and Soil Pollution. 37: 121-129.

Gruen, A. 2007. Homeowners seek safer alternatives to pesticides. The New York Times. April 1, 2007. Available at: http://www.nytimes.com/2007/04/01/nyregion/nyregionspecial2/01wemain.html (verified 01 November 2010).

Hattersley, P. W. 1983. The distribution of C_3 and C_4 grasses in Australia in relation to climate. Oecologia 57:113-128.

Hatzinger, P. B. and M. Alexander. 1997. Biodegradation of organic compounds sequestered in organic solids or in nanopores within silica particles. Environ. Tox. Chem. 16:2215–2221.

Hixson, A. C. 2008. Soil properties affect simazine and saflufenacil fate, behavior, and performance. Ph.D dissertation. Raleigh, NC: North Carolina State University. 226 p.

Horst, G. L., P. J. Shea, N. Christians, D. R. Miller, C. Stuefer-Powell, and S. K. Starrett. 1996. Pesticide dissipation under golf course fairway conditions. Crop Sci. 36:362–370.

Hughes, M. F. 2002. Arsenic toxicity and potential mechanisms of action. Toxicol. Lett. 133:1-16.

Hurto, K. A., A. J. Turgeon, and M. A. Cole. 1979. Degradation of benefin and DCPA in thatch and soil from a Kentucky bluegrass (*Poa pratensis*) turf. Weed Sci. 27:154–157.

Kenna, M. P. 1995. What happens to pesticides applied to golf courses. USGA Green Section Record. 32:1-9.

Khan, B. I., H. M. Solo-Gabriele, B. K. Dubey, T. G. Townsend. And Y. Cai. 2004. Arsenic speciation of solvent-extracted leachate from new and weathered CCA-treated wood. Environ. Sci. Technol. 38:4527-4534.

Kiely, T., D. Donaldson, and A. Grube. 2004. Pesticide industry sales and usage: 2000 and 2001 market estimates. Office of Prevention, Pesticides, and Toxic Substances, U.S. Environmental Protection Agency, Washington, DC.

Kolpin, D. W., J. E. Barbash, and R. J. Gilliom. 1998. Occurrence of pesticides in shallow groundwater of the United States: initial results from the national water-quality assessment program. Environ. Sci. Technol. 32:558-566.

Koppell, G.O. 1994. Toxic fairways: Risking ground water contamination from pesticides on Long Island golf courses. New York State Dep. of Law, New York. Available at http://www.oag.state.ny.us/environment/golf95.html (verified 01 November 2010).

Lin, C. H., Y. S. Tai, D. J. Liu, and M. S. B. Ku. 1993. Photosynthetic mechanisms of weeds in Taiwan. Aust. J. Plant Phys. 20:757-769.

Magri, A. and D. A. Haith. 2009. Pesticide decay in turf: a review of processes and experimental data. J. Environ. Qual. 38:4-12.

Martinez-Ochoa, N., S. W. Mullis, and A. S. Csinos. 2004. First report of yellow nutsedge (*Cyperus esculentus*) and purple nutsedge (*C. rotundus*) in Georgia naturally infected with Impatiens necrotic spot virus (INSV). Plant Dis. 88:771.

McBride, M. B. 1994. Environmental Chemistry of Soils. Oxford University Press Inc., New York, New York. Pp. 45-50.

McCarty, L. B., J. W. Everest, D. W. Hall, T. R. Murphy, F. Yelverton. 2008. Color Atlas of Turfgrass Weeds. Second ed. Hoboken, New Jersey: John Wiley & Sons, Inc.

McElroy, J. S., F. H. Yelverton, M. G. Burton, and C. Brownie. 2005. Habitat delineation of green and false-green kyllinga in turfgrass systems and interrelationship of elevation and edaphic factors. Weed Sci. 53:620-630.

McElroy, J. S., F. H. Yelverton, S. C. Troxler, and J. W. Wilcut. 2003. Selective exposure of yellow and purple nutsedge to CGA-362622, imazaquin, and MSMA. Weed Technol. 17:554-559.

McElroy, J. S., F. H. Yelverton, T. W. Gannon, and J. W. Wilcut. 2004. Foliar vs. soil exposure of green kyllinga (*Kyllinga brevifolia*) and false-green kyllinga (*Kyllinga *gracillima*) to postemergence treatments of CGA-362622, halosulfuron, imazaquin, and MSMA. Weed Technol. 18:145-151.

Milesi, C., S. W. Running, C. D. Elvidge, J. B. Dietz, B. T. Tuttle, and R. R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ. Manage. 36:426-438.

Nam, K., N. Chung, and M. Alexander. 1998. Relationship between organic matter content of soil and the sequestration of phenanthrene. Environ. Sci. Technol. 32:3785–3788.

Nandihalli, U. B. and L. E. Bendixen. 1988. Toxicity and site of uptake of soil-applied imazaquin in yellow and purple nutsedge (*Cyperus esculentus* and *C. rotundus*). Weed Sci. 36:411-416.

Novak, J. M., T. B. Moorman, and C. A. Cambardella. 1997. Atrazine sorption at the field scale in relation to soils and landscape position. J. Environ. Qual. 26:1271–1277.

Qian, Y. L. and R. F. Follett. 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agron. J. 94:930-935.

Reddy, K. N. and L. E. Bendixen. 1988. Toxicity, absorption, translocation, and metabolism of foliar-applied chlorimuron in yellow and purple nutsedge (*Cyperus esculentus* and *C. rotundus*). Weed Sci. 36:707-712.

Schueler, T.R. 2000. Minimizing the impact of golf courses on streams. p. 673–675. *In* T.R. Schueler and H.K. Holland (ed.) The practice of watershed protection. Center for Watershed Protection, Ellicott City, MD.

Shi, W., H. Yao, and D. Bowman. 2006. Soil microbial biomass, activity, and nitrogen transformations in a turfgrass chronosequence. Soil Biology and Biochemistry. 38:311-319.

Smith, J. L. and E. A. Paul. 1988. The role of soil type and vegetation on microbial biomass and activity. Pp. 460-466. *in* F. Megusar and M. Gantar, ed., Perspectives in microbial ecology. Slovene Soc. For Microbiology, Ljubljana, Yugoslavia.

Stoller, E. W. and R. D. Sweet. 1987. Biology and life cycle of purple and yellow nutsedges (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:66-73.

Summerlin, Jr., J. R., H. D. Coble, F. H. Yelverton. 2000. Effect of mowing on perennial sedges. Weed Sci. 48:501-507.

Teeri, J. A. and L. G. Stowe. 1976. Climatic patterns and the distribution of C4 grasses in North America. Oecologia 23:1-12.

Turgeon, A. J. 2008. Turfgrass management. Prentice Hall, Upper Saddle River, New Jersey.

U.S. Environmental Protection Agency. 2010. Organic Arsenicals. Washington, DC. http://www.epa.gov/pesticides/reregistration/organic_arsenicals_fs.html (verified 07 November 2010).

Vencill, W. K., J. S. Richburg, III, J. W. Wilcut, and L. R. Hauf. 1995. Effect of MON-12037 on purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*). Weed Technol. 9:148-152.

Wauchope, R. D., S. Yeh, J. B. Linders, R. Kloskowski, K. Tanaka, B. Rubin, A. Katayama, W. Kordel, Z. Gerstl, M. Lane, and J. B. Unsworth. 2002. Pesticide soil sorption parameters: Theory, measurement, uses, limitations, and reliability. Pest Manage. Sci. 58:419-445.

Weber, J.B. 1991. Fate and behavior of herbicides in soils. South Africa. Applied Plant Sci. 5:28-41.

Weber, J. B., J. A. Best, and J. U. Gonese. 1993. Bioavailability and bioactivity of sorbed organic chemicals in soil. Pp. 153-196. *in* Sorption and degradation of pesticides and organic chemicals in soil. Soil Science Society of America, Madison, Wis.

Wehtje, G. R., R. H. Walker, T. L. Grey, and H. G. Hancock. 1997. Response of purple (*Cyperus rotundus*) and yellow nutsedges (*C. esculentus*) to selective placement of sulfentrazone. Weed Sci. 45:382-387.

DOWNWARD MOBILITY OF SELECT HERBICIDES IN A BERMUDAGRASS FAIRWAY VERSUS BARE GROUND

Travis W. Gannon*, Fred H. Yelverton, Lane P. Tredway, Jerome B. Weber, Rex A. Liebl and Manasi G. Saha

Formatted for submission to Crop Science

T.W. Gannon*, F.H. Yelverton and J.B. Weber, Dep. of Crop Science, North Carolina State Univ., 100 Derieux St., Campus Box 7620, Raleigh, NC 27695; L.P. Tredway, Dep. of Plant Pathology, North Carolina State Univ., 100 Derieux St., Campus Box 7616, Raleigh, NC 27695. R.A. Liebl, Global Herbicide Marketing, BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709. M.G. Saha, Consumer and Environmental Safety, BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709. This research partially fulfilled PhD requirements of corresponding author and was supported by Center for Turfgrass Environmental Research and Education at North Carolina State Univ. Received __________. * Corresponding author (travis_gannon@ncsu.edu).

Abbreviations: As, arsenic; CEC, cation exchange capacity; DAT, days after treatment; DAIT, days after initial treatment; DSMA, disodium methylarsonate; FIFRA, Federal Insecticide, Fungicide, and Rodenticide Act; FQPA, Food Quality Protection Act; GWCP, groundwater contamination potential; Ha, hectare; HM, humic matter; LOD, limit of detection; LOQ, limit of quantitation; MEQ, milliequivalents; MMA, monomethylarsonic acid; MSMA, monosodium methylarsonate; OM, organic matter; PLP, pesticide leaching potential; POST, postemergence; PPB, part per billion; PPI, preplant incorporated; PPM, part per million; PRE, preemergence; UPLC-MS-MS, ultra performance liquid chromatography-mass spectrometry-mass spectrometry; U. S., United States; U. S. EPA, United States Environmental Protection Agency.

Abstract: Experiments were conducted 2007 - 2009 to evaluate downward mobility of select herbicides in an established bermudagrass (*Cynodon dactylon* (L.) Pers.) fairway compared to bare ground. Summer and winter applications were also compared. Evaluated herbicides included atrazine, mesotrione, monosodium methylarsonate, pendimethalin and sulfentrazone. Lysimeters were removed 60 or 120 d after initial treatment and analyzed for parent analyte or total arsenic (monosodium methylarsonate). Generally, herbicides remained in vegetation or surface soil of bermudagrass likely due in part to increased organic matter content and microbial populations whereas they distributed below the surface soil of bare ground. Greater pesticide concentrations were reported after winter applications, likely due to increased biotic and abiotic degradation after summer applications. These data confirm that the downward mobility of soil-mobile herbicides vary among systems and may allow regulatory agencies to treat pesticide fate among systems independently. Further, these data may assist in integrated pest management principles that may reduce adverse environmental effects.

Pesticides are viable management tools in many facets of agriculture, but must be managed carefully to prevent environmental contamination while meeting agronomic goals. In 2001, greater than 460 million kg pesticides were used in the U. S. (United States) (Kiely et al. 2004). Downward pesticide mobility is an important component of environmental fate in crop systems. Occurrence of pesticides in shallow groundwater has been documented in the U. S. in recent years, although 95% of reported concentrations were low (less than 1 $\mu g\ L^{-1}$) (Barbash et al. 2001; Kolpin et al. 1998). Detection of pesticides in groundwater has caused public concern for the safety of freshwater resources (Barbash et al. 2001; Ritter 1990; Williams et al. 1988). The increasing detection of pesticides in groundwater is due in part to increased analytical resolution making it possible to detect pesticides at very low concentrations (Nanita et al. 2009). Additionally, the Food Quality Protection Act (FQPA) of 1996 amended the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) of 1972 changing the way U. S. Environmental Protection Agency (EPA) regulates pesticides (U. S. EPA 1996a). Understanding factors that affect pesticide mobility and being able to predict the likelihood to contaminate groundwater are of utmost importance. To protect groundwater, the U. S. EPA has proposed for states to develop pesticide management plans for pesticides with increased leaching potential (U. S. EPA 1991, 1993).

Traditionally, environmental fate studies have not been specific for each use site, even though characteristics of each cropping system could have a major effect on downward mobility. For example, environmental fate data collected from row crop systems may not be applicable to established turfgrass systems. Currently, some environmental fate studies for turfgrass labels may be conducted in turfgrass environments; however, there remains some extrapolation from other use sites which may lead to inaccurate conclusions.

Pesticide fate in the environment is influenced by many factors. Specifically in soil, fate is based on pesticide and soil physicochemical properties as well as biological properties. Pesticide physicochemical and biological properties include pesticide family, application rate, molecular size, vapor pressure, aqueous solubility, octanol:water partitioning coefficient, soil sorption coefficients, organic carbon sorption coefficients, half-lives, and ionizability, among other properties (Pignatello and Xing 1996; Senesi 1992; Weber 1972; Weber et al. 1973). Soil physicochemical properties which affect pesticide adsorption include soil texture, OM content and type, clay content and type, pH, cation exchange capacity (CEC), soil moisture and bulk density (Dyson et al. 2002; Gan et al. 1996; Hatzinger and Alexander 1995; Piatt and Brusseau 1998; Weber 1991; Wild 1993). Much research has focused on various soil properties, including OM content, humic matter content, clay fraction and type, pH, and CEC and their effect on pesticide fate (Blumhorst et al. 1990; Corbin et al. 1971; Harrison et al. 1976; Weber et al. 1993; Wolcott 1970). Other properties that may influence pesticide fate and persistence include locale and climate, application timing, rainfall and irrigation, previous pesticide applications and cropping system. Differences among winter and summer applications in temperate latitudes include rainfall and irrigation amount, microbial activity, chemical reaction rates, as well as other water relations including evaporation and evapotranspiration rates.

Inherent differences exist among turfgrass and row crop agriculture with respect to pesticide fate. In established turfgrass environments, pesticides are not applied directly to soil, thereby reducing the fraction of pesticide that may leach. Established turfgrass systems are not tilled and during periods of active growth, the turf is mowed and grass clippings are typically returned into the turf canopy. As grass clippings decompose, OM accumulates near the soil surface indicating soils of turfgrass systems generally have higher levels of soil OM that increase with age (Bandaranayake et al. 2003; Hixson 2008; Qian and Follett 2002; Shi et al. 2006). Higher levels of OM may increase pesticide adsorption and reduce plant uptake or leaching (Novak et al. 1997; Weber et al. 1993). Further, established turfgrass systems support larger, more diverse microbial populations which affect pesticide fate (Magri and Haith 2009).

Additional supporting evidence may allow pesticide regulation agencies to view pesticide fate in various systems differently. Additional data may also allow one to devise integrated pest management principles to reduce adverse environmental effects. The objectives of this research were 1) to measure the downward mobility of select herbicides in an established bermudagrass fairway compared to bare soil and 2) determine if application during summer or winter affects downward mobility.

MATERIALS AND METHODS

Field lysimetry. Experiments were conducted at the Sandhills Research Station in Jackson Springs, NC. The soil was a Candor sand soil (sandy, siliceous, thermic grossarenic kandiudult) comprised of 88% sand, 7% silt, and 5% clay (Table 1). Prior to trial initiation, half of a 'Tifway 419' bermudagrass area was treated with glyphosate (N-[phosphonomethyl]glycine) and sod was removed. After sod removal, the area was tilled and fumigated with 90% methyl bromide (bromomethane) and 10% chloropicrin (trichloronitromethane) (448 kg ha^{-1}) at least eight wk prior to experiment initiation. Eight wk were allowed to ensure soil microbial populations were not affected as Yamamoto et al. (2008) reported methyl bromide does not have lasting effects on soil microbial populations.

The bare ground and adjacent 'Tifway 419' bermudagrass area resulted in a modified split plot design.

Field lysimeters were used for experiments as previous research indicates field collected data is preferred compared to data collected in laboratory or chamber environments (Branham et al. 1993). Similarly, Winton and Weber (1996) concluded pesticide mass balance utilizing field lysimeters may approach 97%. Using an inverted post driver, 18 gauge steel lysimeters (15.2 cm diameter, 91.4 cm length) were installed in bermudagrass and bare ground. Trial area contained no slope making runoff and lateral mobility unlikely and lysimeters were installed in the center of 1.5 by 1.5 m plots. During installation, 1.5 cm of lysimeter remained above the soil surface to prevent lateral contamination. The bermudagrass was maintained as a golf course fairway and mown twice per wk (1.9 cm) with clippings returned. While the bare ground plots were not mown, other inputs including irrigation and fertilization were identical to bermudagrass. During summer, areas were irrigated as needed to bring total weekly precipitation to at least 6.4 cm. while no irrigation was applied during winter. This was done to mimic normal turf management practices. Rainfall was recorded onsite by North Carolina Agriculture Research Service (Tables A1 – A4). Also during summer, bermudagrass and bare ground areas received monthly applications of a complete fertilizer providing 48.9 kg N ha^{-1} totaling 195.5 kg N ha^{-1} per season. The bare ground area was kept vegetation free with glyphosate.

Herbicide treatments. Five herbicides were included (Table 2). Each herbicide was applied to a unique plot in bermudagrass and bare ground. Evaluated herbicides included atrazine (AAtrex 4L [Syngenta Crop Protection, Greensboro, NC]), mesotrione (Tenacity [Syngenta Crop Protection, Greensboro, NC]), monosodium methylarsonate (MSMA)

(MSMA [Helena Chemical Company, Collierville, TN]), pendimethalin (Pendulum AquaCap [BASF Corporation, Research Triangle Park, NC]), and sulfentrazone (Dismiss Turf Herbicide [FMC Corporation, Philadelphia, PA]). Application rates are listed in Table 2. Atrazine, pendimethalin and sulfentrazone were applied as a single application, whereas MSMA and mesotrione were applied as split applications at half-rates. MSMA and mesotrione sequentials were applied 7 and 21 DAIT, respectively, which represents typical use regimes.

Summer applications were initiated May 21 2007 or June 02 2008 while bermudagrass was actively growing. Winter applications were initiated November 12 2007 or November 05 2008 when bermudagrass was not actively growing (dormant). Herbicides were applied with a hand-held CO_2-propelled research plot sprayer calibrated to deliver 304 L/ha with four 8002XR flat fan nozzles (TeeJet extended range spray nozzles, Wheaton, IL) on 25 cm spacing at 193 kPa. Immediately after herbicide application, treatments were hand watered with 2.5 cm irrigation to simulate a worst case scenario for downward mobility.

Physicochemical properties of evaluated herbicides are shown in Table 2. Atrazine is a chlorotriazine, weakly basic (pK_a = 1.7) herbicide widely used in many facets of agriculture. Atrazine is commonly used preplant incorporated (PPI), PRE, or early postemergent (POST) for control of many annual broadleaf and grass species (Senseman 2007). Atrazine has a low water solubility (33 mg L^{-1}) and moderate field half-life (60 d) (Senseman 2007). Herbicide residual is important for obtaining season-long weed control; however, this may lead to adverse environmental impacts including groundwater contamination. As stated earlier, speciation of ionizable pesticides is pH-dependent. Atrazine exists primarily in molecular form at near-neutral pH which is more mobile compared to protonated species at more acidic pH. Although atrazine is moderately sorbed to soil and organic carbon, there are numerous reports of atrazine in groundwater (Barbash et al. 2001; Kolpin et al. 1998). This is likely related to its widespread use for many years, moderate persistence and decreased adsorption in alkaline soils (Clay and Koskinen 1990; Goetz et al. 1989; Senseman 2007). Mesotrione is a relatively new triketone herbicide used PRE or early POST for select broadleaf and annual grass control in corn and turf (Senseman 2007). Mesotrione is a weak acid ($pK_a = 3.1$) (Senseman 2007). Although mesotrione is highly water soluble ($K_s = 15{,}000$ mg L^{-1}) and only moderately sorbed to soil and organic carbon, it has been reported unlikely to leach due to its short persistence (Senseman 2007; Weber 2010). MSMA is an organic arsenical herbicide widely used in cotton and turf POST primarily for grass control (Senseman 2007). MSMA is an ionizable herbicide ($pK_a = 4.1$, 9.0) which is highly water soluble ($K_s = 1{,}040{,}000$ mg L^{-1}) (Senseman 2007). While MSMA is moderately to highly sorbed to soil and organic carbon, it may persist 180 d (Senseman 2007). While medium mobility has been reported on sandy soils, MSMA is considered immobile in most soils (Senseman 2007; Weber 2010). An inherent problem with As-based products is As is ubiquitous and converts among various species and valence states making concentration determination difficult. Pendimethalin is a nonionizable dinitroaniline herbicide used PRE in numerous crops as well as turfgrass and forages (Senseman 2007). Although pendimethalin has a moderate half-life, it is considered immobile in soil due to its low water solubility (0.3 mg L^{-1}) and high affinity for soil and organic carbon (Senseman 2007; Weber 2010). Pendimethalin was included in this research as a reference to validate experimental procedures as limited mobility in soil is expected. Sulfentrazone is an ionizable weak acid ($pK_a = 6.6$) aryl triazinone herbicide with a moderate water solubility which is used PRE or POST in soybean, tobacco, and turfgrass (Senseman 2007). Due to sulfentrazone having a pK_a in the range of typical soil pH, it is likely variations in soil pH will significantly affect speciation thereby affecting adsorption and mobility. Sulfentrazone low binding affinity for soil and organic carbon coupled with its persistence causes a moderate potential to leach (Senseman 2007; Weber 2010).

Sampling and pesticide analysis. After approximately 120 d, lysimeters were removed, packaged to prevent disturbance, and transported to Raleigh, NC. Due to the short half-life of mesotrione, additional lysimeters were included for removal 60 DAIT. Lysimeters were cut lengthwise and divided into respective depth increments: 0-2, 2-4, 4-8, 8-15, 15-30, 30-45, 45-60, and 60-90 cm. Precautions were taken to avoid contamination within column depths and among columns. Above ground vegetation from bermudagrass lysimeters was also harvested and retained for analysis. All samples were double-bagged in polyethylene bags, weighed, and stored at -18°C until analysis. A 15 g sample was collected and placed in a drying oven at 105°C for 24 h to determine gravimetric water content to allow residue adjustment to reflect concentration for dry soil.

Prior to analysis, samples were thawed for 8 h at room temperature in an air-tight container. Samples were milled (Fitzmill homoloid model J [Fitzpatrick, Elmhurst, IL]) by mixing with dry ice through 1 mm screen. Samples were immediately micro-milled (Retsch mill ZM200 [Retsch Inc., Newtown, PA]) through a 1 mm ring sieve using liquid nitrogen to cool the rotor. After milling, samples were placed in unsealed polyethylene bags and allowed to sublime for 24 hours. After sublimation, samples were homogenized and stored at -18°C until analysis.

Herbicides were extracted according to published environmental chemistry methods. Atrazine was extracted according to U. S. EPA Method Number 87-1 with modifications as described below (U. S. EPA 1987) (Figure 1). Ten grams soil was placed in a centrifuge bottle (175 mL polypropylene conical bottom centrifuge bottle, Nalge Nunc International Corp., Rochester, NY)] and 50 mL acetone:n-hexane (1:1) was added and shook on an orbital shaker (IKA KS 501 Digital Shaker [IKA Works, Inc., Wilmington, NC]) for 30 min at 240 rpm. Sample was centrifuged for 10 min at 4000 rpm (Beckman GS-6 Centrifuge [Beckman Coulter, Inc., Brea, CA]) and supernatant was decanted. Another 50 mL acetone:n-hexane (1:1) was added and shaking, centrifugation, and decanting were repeated as previously described. Supernatant was combined with previous extraction and solution was brought to 100 mL final volume with acetone:n-hexane (1:1). One mL aliquot supernatant was removed, evaporated to dryness with nitrogen evaporator (N-Evap Nitrogen Evaporator Model N112 [Organomation Associates, Inc., Berlin, MA]), and reconstituted in 4 mL methanol:water (1:1). Solution was filtered using a 0.45 µm nylon membrane filter (Gelman Science, Ann Arbor, MI), vialed and analyzed by ultra performance liquid chromatography-mass spectrometry-mass spectrometry (UPLC-MS-MS).

Mesotrione was extracted according to U. S. EPA Method Number 445051-26 with modifications as described below (U. S. EPA 1997a) (Figure 2). Ten grams soil was placed in a 175 mL polypropylene conical bottom centrifuge bottle and 50 mL 0.05 M ammonium hydroxide was added and shook on an orbital shaker for 30 min at 240 rpm. Sample was centrifuged for 10 min at 4000 rpm and supernatant was decanted. Thirty milliliters supernatant was transferred to a 50 mL centrifuge tube and the pH was adjusted to 3.5 – 4.0 with formic acid. Sample was centrifuged for 10 min. at 4000 rpm and allowed to stand for

15 min prior to filtering through 0.45 µm syringe filter. Sample was vialed and analyzed by UPLC-MS-MS.

Attempts to extract and analyze MSMA samples with UPLC-MS-MS were unsuccessful. Therefore MSMA-treated samples were analyzed for total arsenic (As) and background levels were subtracted to determine As levels that were presumably due to MSMA applications. Background As levels were determined from nontreated lysimeters that were collected fall 2007. Soils were digested according to U. S. EPA protocol number SW846, method 3050B (U. S. EPA 1996b) (Figure 3). Two grams soil was placed in digestion tubes, then 15 mL deionized water:nitric acid (1:1) was added and allowed to stand for 16 h. Capped tubes were heated to 95° C for 15 min and allowed to cool prior to adding 5 mL 15.8 M nitric acid. Tubes were vortexed, heated to 95° C for 30 min, and allowed to cool. Five additional mL 15.8 M nitric acid was added, vortexed, heated, and cooled as previously described. Uncapped tubes were heated to 95° C for two h and allowed to cool prior to adding 3 mL deionized water and 2 mL 30% hydrogen peroxide and heated to 95° C until effervescence subsided. Four milliliters 30% hydrogen peroxide was added incrementally (1 mL) to allow effervescence. Tubes were vortexed, heated to 95° C for 2 h, and allowed to cool. Ten milliliters 12.1 M hydrochloric acid was added, heated to 95° C for 15 min, and allowed to cool prior to filtering through Whatman #41 paper. Digestate was brought to 50 mL final volume and diluted 1:5 with deionized water, vialed, and analyzed with mass spectrometry.

Pendimethalin was extracted according to U. S. EPA Method Number 445276-01 with modifications as described below (U. S. EPA 1996c) (Figure 4). Ten grams soil was placed in a 175 mL polypropylene conical bottom centrifuge bottle and 25 mL deionized water was added and swirled by hand for 15 s. Seventy-five milliliters 2% acidic methanol was added and shook on an orbital shaker for 1 h at 240 rpm. Sample was centrifuged for 10 min at 4000 rpm and supernatant was decanted. Sample was filtered through 0.45 µm syringe filter, vialed, and analyzed by UPLC-MS-MS.

Sulfentrazone was extracted according to Ohmes and Mueller (1999) with modifications as described below (Figure 5). Ten grams soil was placed in a 175 mL polypropylene conical bottom centrifuge bottle. Eighty milliliters methanol was added and shook on an orbital shaker for 1 h at 240 rpm. Sample was centrifuged for 10 min at 4000 rpm and supernatant was decanted. Solution was filtered through a 0.45 µm nylon membrane filter and sample was diluted 1:1 with methanol:water (1:1). Sample was vialed and analyzed by UPLC-MS-MS.

Atrazine, mesotrione, pendimethalin and sulfentrazone samples were analyzed by triple quadrupole UPLC-MS-MS within 12 h of extraction (Perkin-Elmer Sciex API 3000 [Perkin-Elmer, Waltham, MA]). The column was a C_{18} (Columbus 100 mm x 2.0 mm, 5 µm [Phenomenex, Torrance, CA]). The injection parameters were as follows: volume: 10 µL, temperature: 500°C, mobile phase A: water with 0.1% formic acid, mobile phase B: methanol with 0.1% formic acid, and flow rate: 450 µL minute^{-1}. Herbicide residues were quantified from concentration calculations based on peak area measurements using a calibration curve and Analyst 1.4.2 software (SB Sciex [Foster City, CA]). The standard curve was obtained by direct injection of 10 µL of standard in the range of 0.125 to 10 ng mL^{-1}. Calibration curves were prepared by plotting peak area versus concentration using a linear relationship. Standard solutions were prepared and kept refrigerated and used no longer than one month to alleviate storage stability concerns. The limit of quantitation (LOQ) was defined as the lowest fortification successfully evaluated and was 0.01 mg kg^{-1} or part per million (ppm) while the limit of detection (LOD) was 2.0 μg kg^{-1} or part per billion (ppb) for each analyte excluding MSMA. The LOQ and LOD for MSMA was 0.5 and 0.05 mg kg^{-1}, respectively, or part per million (ppm). The LOD and LOQ were established based on calibration curves and signal to noise ratios when confirming chromatographic methods. Instrument checks were routinely performed as well to assure peak enhancement or suppression were not occurring and calibration standards were included after every five samples.

Extraction efficiencies were verified each time samples were analyzed by fortifying control soils and allowing the solvent to evaporate. Low and high fortifications were included each time samples were analyzed. Fortification samples were prepared by adding appropriate volume parent material standard solution by volumetric pipette onto control soil and extracting as previously described. A control spike was also included in each sample set by spiking a control supernatant to assure analyte suppression did not occur. Analyte concentration was calculated based on extraction volume per mass soil adjusted for soil moisture content and μg analyte kg^{-1} dry soil was reported. Excluding MSMA, pesticide concentrations are reported as μg analyte kg^{-1} dry soil (ppb). Total As concentrations (mg As kg^{-1}) (ppm) are reported for MSMA treatments. Lysimeter total and initial concentrations as well as total as percent of initial concentration were determined. Surface (0 – 4 cm) and subsurface (> 4 cm) concentrations are also reported as concentration and as percent of lysimeter total.

Soil physical and chemical properties. In the established bermudagrass system, the thatch layer was approximately 4 cm in depth. Particle size analysis was performed using the hydrometer method (Bouyoucus 1962; Gee and Bauder 1986) (Table 1). Samples were also analyzed for CEC, OM content, and pH. Organic matter content was determined by Walkley-Black method (Sims and Wolf 1995). Soil pH was measured using a glass electrode pH meter of 1:1 soil:water utilizing standards. Cation exchange capacity (milliequivalents (meq)/100 g soil) was determined by summing base cations using Mehlich III extraction and the quantity of exchangeable acidity determined using Mehlich buffer method (Mehlich 1984b).

Experimental design and analysis. Pesticide treatments were arranged in a modified split-plot design with unique bermudagrass and bare ground plots. The experiment was completed once in each of two y (2007/2008 or 2008/2009) and included applications during summer or winter. The data were subjected to analysis of variance (ANOVA) using mixed model procedures and analyzed for effect of system, season, replication, and y (SAS Institute 2010). Analysis of variance was conducted to determine if significant main effects or interactions involving system, season, replication, and year for each herbicide and depth increment were present. Samples from 0-2, 2-4, 4-8, 8-15, and 15-30 cm depths were always analyzed. Deeper samples including 30-45, 45-60, and 60-90 cm were analyzed iteratively from shallow to deep until two consecutive nondetects or concentrations below LOD were reported.

RESULTS AND DISCUSSION

In general, herbicides remained in the surface soil (0 – 4 cm) or vegetation of established bermudagrass while they distributed beyond the surface soil of bare ground. Additionally, greater herbicide concentrations were reported after winter applications compared to summer, indicating that herbicides were more persistent after winter applications.

Atrazine concentrations after summer applications were minimal (< 0.1% of initial), regardless of system (Table 3). However, after winter atrazine applications, greater than twice as much atrazine was recovered in dormant turf (13% of initial) compared to bare ground (6 % of initial). Furthermore, of total atrazine recovered, 90% was recovered in surface soil or above ground vegetation of dormant turf whereas only 49% was recovered in surface soil of bare ground. Although, the greatest concentration (114 $\mu g\ kg^{-1}$) was present in the shallowest depth (0 – 2 cm), atrazine distributed uniformly in 0 – 15 cm depths in bare ground. In dormant turf, the highest concentration (337 $\mu g\ kg^{-1}$) was present in the shallowest soil depth while atrazine concentrations were reduced in depths > 2 cm. Atrazine was not reported in depths > 45 cm, regardless of system or season indicating atrazine is not likely to leach to groundwater under similar soil application and climatic conditions. Brejda et al. (1988) reported minimal atrazine downward movement through a Kentucky bluegrass pasture with a shallow water table in the Nebraska sandhills. Contrarily, Bowman (1989) reported little atrazine appeared in effluent of bare ground sand field lysimeters (70 cm deep) after 84 d when supplemental watering was provided. Other research has reported atrazine leaching through lysimeters at varying times (Bowman 1989; Weber et al. 1993). Cummings et al. (2009) reported that simazine, another triazine herbicide, concentration was greatest in the leachate of dormant bermudagrass compared to actively growing bermudagrass and fallow soil. Further, Cummings et al. (2009) suggested simazine leaching in dormant bermudagrass may be the result of channeling in the soil profile created by the roots allowing greater infiltration rates, compared to fallow or bare ground lysimeters. These data and previous research indicate potential downward mobility of atrazine is variable and dependent on many factors. Weber et al. (1993) concluded atrazine mobility was highly correlated with soil texture, OM and humic matter content as well as soil pH. Within this research, soil texture and soil pH were similar among systems, while OM content varied and likely had the greatest influence on atrazine mobility of these soil factors. As previously mentioned, OM content has the greatest impact on pesticide adsorption and downward mobility (Alexander 2000; Farenhorst 2006; Hatzinger and Alexander 1997; Nam et al. 1998; Wauchope et al. 2002; Weber et al. 1993).

Mesotrione concentrations from soil depths < 30 cm were similar to concentrations at the 0 – 2 cm depth in both bare ground and actively growing bermudagrass, indicating mesotrione distributes uniformly through shallow depths within 60 d of summer applications (Table 4). Mesotrione is root and shoot absorbed and readily metabolized by plants and soil microorganisms (Senseman 2007). Bare ground lysimeter total captured was 3.5 times greater than actively growing bermudagrass system, indicating plant uptake and metabolism and microbial populations present in established turfgrass likely degrade significant amounts of mesotrione. Of recovered mesotrione, only 29% was present in the surface soil of the bare ground compared to 64% in the surface soil or above ground vegetation of actively growing bermudagrass. After winter applications, the greatest concentration was observed in the 0 – 2 cm depth of the bare ground system while concentrations in depths > 4 cm were reduced. In dormant turf conditions, similar concentrations were reported in above ground vegetation and 0 – 2 cm depth while concentrations in depths > 2 cm were reduced by > 60%. Of recovered mesotrione after winter applications, 66% was recovered in surface soil of bare ground while 90% was recovered in surface soil or above ground vegetation of dormant bermudagrass, indicating although bermudagrass was dormant, the system was capable of retaining mesotrione near the soil surface. Mesotrione was not detected at depths > 30 cm, regardless of season or system.

Although minimal (< 1% of initial) mesotrione was recovered 120 d after summer applications, mesotrione distributed uniformly through 30 cm of bare ground (Table 5). Conversely, mesotrione concentrations were reduced at depths > 2 cm in established bermudagrass compared to 0 – 2 cm. Similar to summer applications, mesotrione distributed uniformly through 30 cm after winter applications in bare ground. Greatest concentrations were present in the 0 – 2 cm depth or above ground vegetation of dormant bermudagrass, indicating that although bermudagrass was dormant, the system retained mesotrione near the soil surface and prevented it from distributing to depths > 4 cm. After winter applications, only 56% of recovered mesotrione was present in surface soil of bare ground while 80% was present in surface soil or above ground vegetation of dormant bermudagrass. Similar to lysimeters harvested 60 d after application, mesotrione was not reported in depths > 30 cm 120 d after application, regardless of system or season.

Hixson et al. (2008) concluded mesotrione had greater soil mobility than atrazine while these data indicate less mesotrione was present in the subsurface soil of bare ground after winter. Contrary to these data, Rouchaud et al. (2000) reported no significant mesotrione residues in the 15 – 20 cm soil layer of corn fields on four soils in Belgium;

however, they only utilized 0.15 kg ha^{-1} mesotrione compared to 0.6 kg ha^{-1} we applied. Further, Rouchaud et al. (2000) concluded mesotrione remained in the 0 – 4 cm soil depth two months after application while it distributed through 15 cm later in the season. Soil OM content and soil solution pH are the predominant variables affecting mesotrione adsorption, with greater adsorption at lower pH and higher OM content (Dyson et al. 2002; Shaner et al. 2006). In this research, soil pH was similar among systems at < 15 cm depths, suggesting variation in pH likely did not affect mesotrione mobility; however, soil OM content among systems varied greatly, particularly in the surface soil (0 – 4 cm). Soil OM content in the surface soil averaged 1.4 and 3.4% for bare ground and established bermudagrass system, respectively, likely constituting much of the difference in mesotrione mobility among systems (Table 1).

While As-containing pesticides have been used in agriculture in the U.S. for over 100 y, there is currently much debate around the status of organoarsenical pesticides (Onken and Hossner 1996). U.S. EPA has an organoarsenical phase-out planned for the turfgrass industry, with sales permitted through 2012 and use of existing stock through 2013 with imposed restrictions while use in cotton has been declared eligible for reregistration (U. S. EPA 2010). Much of the debate around the status and future of organoarsenicals is based on conversion of organic arsenicals to species which may be more toxic. Inorganic arsenic compounds include trivalent (arsenic trioxide) and pentavalent forms (arsenic acid, sodium arsenate, lead arsenate, and calcium arsenate). Organoarsenical compounds include methanearsonic acid, MSMA, dimethylarsonic acid (DMA), and disodium methanearsonate (DSMA). Bednar et al. (2002) reported biotic and abiotic degradation of organoarsenicals in soil and water can produce inorganic As species including arsenite and arsenate although concentrations did not exceed 10 μg L^{-1} which was the current maximum contaminant level. Similarly, Whitmore et al. (2008) concluded MSMA may convert rapidly to inorganic As species in soil and are readily leachable.

Analytical techniques prevented sample analysis for MSMA or monomethylarsonic acid (MMA); therefore, samples were analyzed for total arsenic (As) and background levels were deducted for respective depth increment to report As concentration assumingly due to MSMA applications (Table 6). The authors feel several issues confounded the results, including lower than expected initial concentrations as well as higher than expected As concentrations in above ground vegetation of bermudagrass lysimeters. Based on theoretical calculations, 6 – 9 mg As kg^{-1} was anticipated whereas we only reported 3.7 mg As kg^{-1}. Higher As concentrations in above ground vegetation may indicate that bermudagrass absorbs and accumulates various forms of As. Interestingly, the highest As concentrations were reported for above ground vegetation in established bermudagrass, regardless of season. Previous research indicates As concentration in plant leaves may be as high as the soil level on which plants were grown (Weaver et al. 1984). Increased As concentrations were not reported deeper than 45 cm, regardless of system or season. After summer MSMA applications in bare ground, similar As concentrations were reported 0 – 8 cm, while reduced concentrations were observed in depths > 8 cm compared to 0 – 2 cm. In established bermudagrass, As concentrations deeper than 4 cm were reduced compared to 0 – 2 cm. Of the As assumingly due to MSMA applications, 58% was present in surface soil of bare ground system compared to 84% in actively growing bermudagrass. After winter applications, the highest As concentration was reported in 0 – 2 cm depth of bare ground while concentrations below 2 cm were reduced. Similarly, in dormant bermudagrass, reported As concentrations below 2 cm were reduced compared to 0 – 2 cm depth indicating although MSMA applications led to increased As concentrations through 15 cm, As did not distribute uniformly and highest concentrations were reported near the soil surface. Of total As, 70% was present in surface soil of bare ground compared to 95% in actively growing bermudagrass after winter application. Previous research suggests organoarsenical herbicides may contaminate groundwater under certain conditions and concluded fate and transport of As compounds is largely dependent on species of As (Cai et al. 2002).

Pendimethalin was included as a standard as previous research indicates minimal soil mobility and risk of groundwater contamination in managed turfgrass systems (Schleicher et al. 1995; Stahnke et al. 1991). Excluding bare ground during summer, reported pendimethalin concentrations were highest in the 0 – 2 cm depth indicating limited downward mobility occurred (Table 7). Total reported concentrations under bare ground lysimeters were two times greater than actively growing bermudagrass indicating plant uptake and metabolism and microbial populations present in actively growing bermudagrass likely degrade significant amounts of pendimethalin. Pendimethalin has high soil and organic carbon binding coefficients indicating it has low potential to leach in soil (Senseman 2007). Further, pendimethalin is absorbed by roots and coleoptiles and is highly lipophilic; therefore, it partitions into membranes and other lipid components readily (Senseman 2007). While basipetal and acropetal pendimethalin movement occurs, translocation from root into shoot is minimal (Durgesha 1994). Of recovered pendimethalin, 87 and 84% were recovered in surface soil or above ground vegetation of bare ground and actively growing bermudagrass, respectively, indicating minimal downward mobility. Similarly, 96 and 98% of recovered pendimethalin was recovered in surface soil or above ground vegetation of bare ground and dormant bermudagrass, respectively after winter applications, while pendimethalin was not detected deeper than 30 cm, regardless of system or season.

Within this research, sulfentrazone was the only evaluated compound which the highest reported concentration was not in the 0 – 2 cm depth under each system and season (Table 8). After summer applications in bare ground, the highest sulfentrazone concentration was reported in the 8 – 15 cm depth (42 $\mu g\ kg^{-1}$), greater than 5 times the concentration reported in 0 – 2 cm depth (8 $\mu g\ kg^{-1}$). In actively growing bermudagrass, sulfentrazone distributed uniformly from the surface through 30 cm. Sulfentrazone recovered in bermudagrass was reduced by > 70% compared to bare ground suggesting bermudagrass and microbial populations absorbed and metabolized or mineralized significant amount of sulfentrazone. Of recovered sulfentrazone, only 19% was present in the surface soil of bare ground compared to 45% in the surface soil or above ground vegetation of actively growing bermudagrass. After winter applications, 42% of recovered sulfentrazone was present in the surface soil of bare ground compared to 89% in the surface soil or above ground vegetation of dormant bermudagrass. These data indicate although sulfentrazone is moderately mobile under evaluated conditions, an established turfgrass system effectively reduces leaching beyond the surface soil regardless of season.

Sulfentrazone has a low organic carbon and soil binding coefficient and moderate aqueous solubility resulting in moderate leaching potential (Senseman 2007; Weber 2010). Sulfentrazone has been reported to injure crops in unpredictable patterns assumingly due to carryover (Ferrell et al. 2003; U.S. EPA 1997b). Higher sulfentrazone sorption and lower desorption has been reported for soils with increased OM (Reddy and Locke 1998) while Grey et al. (1997) indicated pH had the greatest effect on adsorption and mobility.

Additionally, previous research suggests sulfentrazone may be more persistent in areas that have not been previously exposed to sulfentrazone as native microbial populations have demonstrated poor adaptability to sulfentrazone (Reddy and Locke 1998). Previous research has reported sulfentrazone leaching is unlikely under normal conditions (Ohmes and Mueller 2007). Further, Ohmes and Mueller (2007) concluded no clear relationship existed among sulfentrazone adsorption and mobility in evaluated soils.

Excluding MSMA, greater herbicide concentrations were reported after winter applications compared to summer (Table 9). Differences ranged from 2.7 (mesotrione – 60 DAIT) to 84 (atrazine) times greater concentrations after winter applications. Previous research has reported greater pesticide concentrations after winter compared to summer applications (Cummings 2004). Similarly, Brejda et al. (1988) concluded late season atrazine applications may have greater potential to contaminate groundwater compared to spring applications. This is likely due at least in part to increased microbial activity, increased chemical degradation, and increased absorption and detoxification in established bermudagrass during summer. Previous research has reported hydrolysis rates of select pesticides are pH and temperature-dependent (Zheng et al. 2008). Similarly, microbial degradation of pesticides is greater at higher temperatures typical of summer applications.

The above data provide useful information about potential downward mobility of five commonly used turfgrass herbicides in soil. Our results, in addition to previous research, indicates downward herbicide mobility is variable and depends on many factors. In general, evaluated herbicides distributed beyond surface soil of bare ground while the majority of recovered analytes remained in the surface soil or above ground vegetation of established bermudagrass. Even with sulfentrazone, which displayed significant downward mobility, established bermudagrass reduced the fraction that distributed below surface soil. These data confirm the fate of pesticides should not be assumed to behave similarly across various systems, notably row crop agriculture and turfgrasses. Pesticide fate is of utmost importance and may be used to predict potential off-target movement, specifically downward mobility towards groundwater. These data also provide more information to further develop our understanding and ability to characterize downward mobility based on physicochemical and biological properties. One may also use these data to devise comprehensive integrated pest management strategies to minimize off-target movement by altering application time during periods of active growth and increased microbial activity.

ACKNOWLEDGMENTS

The authors express appreciation to Jeff Chandler, Jared Hoyle, Mark Thompson and Leon Warren for technical assistance and Dr. Consuelo Arellano for statistical assistance.

LITERATURE CITED

Alexander, M. 2000. Aging, bioavailability, and overestimation of risk from environmental contaminants. Environ. Sci. Technol. 34:4259–4265.

Bandaranayake, W., Y. L. Qian, W. J. Parton, D. S. Ojima, and R. F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agron. J. 95:558-563.

Barbash, D. E., G. P. Thelin, D. W. Kolpin, and R. J. Gilliom. 2001. Major herbicides in ground water: results from the National Water-Quality Assessment. J. Environ. Qual. 30:831-845.

Bednar, A. J., J. R. Garbarino, J. F. Ranville, and T. R. Wildeman. 2002. Presence of organoarsenicals used in cotton production in agricultural water and soil of the southern United States. J. Agric. Food Chem. 50:7340-7344.

Blumhorst, M. R., J. B. Weber, and L. R. Swain. 1990. Efficacy of selected herbicides as influenced by soil properties. Weed Technol. 4:279-283.

Bouyoucos, G. J. 1962. Hydrometer method improved for making particle size analyses of soils. Agron. J. 54:464-465.

Bowman, B. T. 1989. Mobility and persistence of the herbicides atrazine, metolochlor, and terbuthylazine in plainfield sand determined using field lysimeters. Envir. Tox. Chem. 8:485-491.

Branham, B. E., D. R. Smitley, and E. D. Miltner. 1993. Pesticide fate in turf. Pp. 156-167. *in* K. D. Racke and A. R. Leslie, eds. Pesticides in urban environments. American Chemical Society. Washington, DC.

Brejda, J. J., P. J. Shea, L. E. Moser, and S. S. Waller. 1988. Atrazine dissipation and off-plot movement in a Nebraska Sandhills subirrigated meadow. J. Range Man. 41:416-420.

Cai, Y., J. C. Cabrera, M. Georgiadis, and K. Jayachandran. 2002. Assessment of arsenic mobility in the soils of some golf courses in south Florida. Sci. Total Environ. 291:123-134.

Clay, S. A. and W. C. Koskinen. 1990. Adsorption and desportion of atrazine, hydroxyatrazine, and s-glutathione atrazine in two soils. Weed Sci. 38:262-266.

Corbin, R. T., R. P. Upchurch, and F. L. Selman. 1971. Influence of pH on the phytotoxicity of herbicides in the soil. Weed Sci. 19:233–239.

Cummings, H. D. 2004. Pesticide downward movement in a bermudagrass system compared with movement in a fallow system. Ph.D dissertation. Raleigh, NC: North Carolina State University. 208 p.

Cummings, H. D., J. B. Weber, F. H. Yelverton, and R. B. Leidy. 2009. Downward mobility of ^{14}C-labeled simazine in a bermudagrass system vs. a fallow soil system. Crop sci. 49:704-713.

Durgesha, M. 1994. Absorption, translocation and metabolism of fluchloralin in groundnut (*Arachis hypogaea*) and pigweed (*Amaranthus viridis*). Crop protection 13:286-290.

Dyson, J. S., S. Beulke, C. D. Brown, and M. C. G. Lane. 2002. Adsorption and degradation of the weak acid mesotrione in soil and environmental fate implications. J. Environ. Qual. 31:613-618.

Farenhorst, A. 2006. Importance of soil organic matter fractions in soil-landscape and regional assessments of pesticide sorption and leaching in soil. Soil Sci. Am. J. 70:1005-1012.

Ferrell, J. A., W. W. Witt, and W. K. Vencill. 2003. Sulfentrazone absorption by plant roots increases as soil or solution pH decreases. Weed Sci. 51:826-830.

Gan, J., S. R. Yates, D. Wang, and W. F. Spencer. 1996. Effect of soil factors on methyl bromide volatilization after soil application. Environ. Sci. Technol. 30:1629-1636.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. Page 383-411. *In* A. Klute, Ed., Methods of Soil Analysis, Agron. Series 9, Part 1, 2nd ed. American Society of Agronomy, Madison, WI.

Goetz, A. J., R. H. Walker, G. Wehtje, and B. F. Hajek. 1989. Sorption and mobility of chlorimuron in Alabama soils. Weed Sci. 37:428-433.

Grey, T. L., R. H. Walker, G. R. Wehtje, and H. G. Hancock. 1997. Sulfentrazone adsorption and mobility as affected by soil and pH. Weed Sci. 45:733–738.

Harrison, G. W., J. B. Weber, and J. V. Baird. 1976. Herbicide phytotoxicity as affected by selected properties of North Carolina soils. Weed Sci. 24:120-126.

Hatzinger, P. B. and M. Alexander. 1995. Effect of ageing of chemicals in soil on their biodegradability and extractability. Environ. Sci. Technol. 29:537-545.

Hatzinger, P. B. and M. Alexander. 1997. Biodegradation of organic compounds sequestered in organic solids or in nanopores within silica particles. Environ. Tox. Chem. 16:2215–2221.

Hixson, A. C. 2008. Soil properties affect simazine and saflufenacil fate, behavior, and performance. Ph.D dissertation. Raleigh, NC: North Carolina State University. 226 p.

Kiely, T., D. Donaldson, and A. Grube. 2004. Pesticide industry sales and usage: 2000 and 2001 market estimates. Office of Prevention, Pesticides, and Toxic Substances, U.S. Environmental Protection Agency, Washington, DC.

Kolpin, D. W., J. E. Barbash, and R. J. Gilliom. 1998. Occurrence of pesticides in shallow groundwater of the United States: initial results from the national water-quality assessment program. Environ. Sci. Technol. 32:558-566.

Magri, A. and D. A. Haith. 2009. Pesticide decay in turf: a review of processes and experimental data. J. Environ. Qual. 38:4-12.

Mehlich, A. 1984a. Photometric determination of humic matter in soils, a proposed method. Common. Soil Sci. Plant Anal. 15:1417-1422.

Mehlich, A. 1984b. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Nam, K., N. Chung, and M. Alexander. 1998. Relationship between organic matter content of soil and the sequestration of phenanthrene. Environ. Sci. Technol. 32:3785–3788.

Nanita, S. C. 2009. High-throughput pesticide residue quantitative analysis achieved by tandem mass spectrometry with automated flow injection. Anal. Chem. 81:3134-3142.

Novak, J. M., T. B. Moorman, and C. A. Cambardella. 1997. Atrazine sorption at the field scale in relation to soils and landscape position. J. Environ. Qual. 26:1271–1277.

Ohmes, G. A. and T. C. Mueller. 1999. Liquid chromatographic determination of sulfentrazone in soil. J. Ass. Anal. Chem. 82:1214-1216.

Ohmes, G. A. and T. C. Mueller. 2007. Sulfentrazone adsorption and mobility in surface soil of the Southern United States. Weed Technol. 21:796-800.

Onken, B. M. and L. R. Hossner. 1996. Determination of arsenic species in soil solution under flooded conditions. Soil Sci. Soc. Am. J. 60:1385-1392.

Piatt, J. J. and M. L. Brusseau. 1998. Rate limiting sorption of hydrophobic organic compounds by soils with well characterized organic matter. Environ. Sci. Technol. 32:1604-1608.

Pignatello, J. J. and B. Xing. 1996. Mechanisms of slow sorption of organic chemicals to natural particles. Environ. Sci. Technol. 30: 1-11.

Qian, Y. L. and R. F. Follett. 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agron. J. 94:930-935.

Reddy, K. N. and M. A. Locke. 1998. Sulfentrazone sorption, desorption, and mineralization in soil from two tillage systems. Weed Sci. 46:494-500.

Ritter, W. F. 1990. Pesticide contamination of ground water in the United States – a review. J. Environ. Sci. and Health. Part. B, Pesticides, food contaminants, and agricultural wastes. 25:1-29.

Rouchaud, J., O. Neus, H. Eelen, and R. Bulcke. 2000. Dissipation and mobility of the herbicide mesotrione in the soil of corn crops [abstract]. In: Proceedings of the 52nd International Symposium on Crop Protection; May 09 2000; Gent, Belgium; 2000. Pp. 51-58.

SAS Institute Inc. 2010. SAS version 9.2. Cary, NC.

Schleicher, L. C., P. J. Shea, R. N. Stougaard, and D. R. Tupy. 1995. Efficacy and dissipation of dithiopyr and pendimethalin in perennial ryegrass (*Lolium perenne*) turf. Weed Sci. 43:140-148.

Senesi, N. 1992. Binding mechanisms of pesticides to soil humic substances. Science of the Total Environment. 123/124:63-76.

Senseman, S. A. Ed. 2007. Herbicide Handbook. 9th Edition. Weed Science Society of America, 458 pp.

Shaner, D. L., G. Brunk, S. Nissen, and P. Westra. 2006. Adsorption and degradation of mesotrione in four soils. North Central Weed Sci. Soc. Proc. December 12 2006. Milwaukee, WI.

Shi, W., H. Yao, and D. Bowman. 2006. Soil microbial biomass, activity, and nitrogen transformations in a turfgrass chronosequence. Soil Biology and Biochemistry. 38:311-319.

Sims, J.T. and A.M. Wolf (eds.). 1995. Recommended Soil Testing Procedures for the Northeastern United States. Northeastern Regional Publication No. 493 (revised). University of Delaware Agric. Exp. Stat., Newark, DE.

Stahnke, G. K., P. J. Shea, D. R. Tupy, R. N. Stougaard, and R. C. Shearman. 1991. Pendimethalin dissipation in Kentucky bluegrass turf. Weed Sci. 39:97-103.

U.S. Environmental Protection Agency. 1987. Environmental Chemistry Methods: Simazine. Washington, DC. www.epa.gov/pesticides/methods/ecmmethods/406144-14-S.pdf (verified 01 November 2010).

U.S. Environmental Protection Agency. 1991. Pesticides and groundwater strategy. USEPA Rep. 21T-1022. USEPA, Office of pesticides and Toxic Substances, Washington DC.

U.S. Environmental Protection Agency. 1993. Guidance for pesticides and ground water state management plans. USEPA Rep. 735-B-93-005a. USEPA, Office of Prevention, Pesticides, and Toxic Substances, Washington DC.

U.S. Environmental Protection Agency. 1996a. Federal insecticide, fungicide, and rodenticide act (FIFRA). Washington, DC. http://www.epa.gov/oecaagct/lfra.html (verified 01 November 2010).

U.S. Environmental Protection Agency. 1996b. Acid Digestion of Sediments, Sludges, and Soils. Washington, DC. http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/3050b.pdf (verified 01 November 2010).

U.S. Environmental Protection Agency. 1996c. Environmental Chemistry Methods: Pendimethalin. Washington, DC. www.epa.gov/pesticides/methods/ecmmethods/445276-01-SW.pdf (verified 01 November 2010).

U.S. Environmental Protection Agency. 1997a. Environmental Chemistry Methods: Mesotrione. Washington, DC. www.epa.gov/pesticides/methods/ecmmethods/445051-26-S.pdf (verified 01 November 2010).

U.S. Environmental Protection Agency. 1997b. Pesticide fact sheet: sulfentrazone. USEPA, Office of Prevention, Pesticides, and Toxic Substances, Washington DC U.S. Environmental Protection Agency. 2010. Organic Arsenicals. Washington, DC. http://www.epa.gov/pesticides/reregistration/organic_arsenicals_fs.html (verified 07 November 2010).

Wauchope, R. D., S. Yeh, J. B. Linders, R. Kloskowski, K. Tanaka, B. Rubin, A. Katayama, W. Kordel, Z. Gerstl, M. Lane, and J. B. Unsworth. 2002. Pesticide soil sorption parameters: Theory, measurement, uses, limitations, and reliability. Pest Manage. Sci. 58:419-445.

Weaver, R. W., J. R. Melton, D. Wang, and R. L. Duble. 1984. Uptake of arsenic and mercury from soil by bermudagrass. Environ. Pollut. 33:133-142.

Weber, J. B. 1972. Interaction of organic pesticides with particulate matter in aquatic and soil systems. Pp. 55-120. *in* Fate of Organic Pesticides in the Aquatic Environment, pp. 55-120. American Chemical Society.

Weber, J. B. T. J. Monaco, and A. D. Worsham. 1973. What happens to herbicides in the environment? Weeds today 4:16-17.

Weber, J.B. 1991. Fate and behavior of herbicides in soils. South Africa. Applied Plant Sci. 5:28-41.

Weber, J. B., J. A. Best, and J. U. Gonese. 1993. Bioavailability and bioactivity of sorbed organic chemicals in soil. Pp. 153-196. *in* Sorption and degradation of pesticides and organic chemicals in soil. Soil Science Society of America, Madison, Wis.

Weber, J. B. 2010. Relative pesticide leaching potential (PLP) indices and ratings for commonly used pesticides, relative pesticide leaching potential (PLP) indices and ratings for commonly used pesticides, groundwater contamination potential (GWCP) risk of pesticide-soil combinations. Pp. 12 – 16. *in* S. J. Toth Jr., ed., North Carolina Agricultural Chemicals Manual, North Carolina State University, Raleigh, NC.

Whitmore, T. J., M. A. Riedinger-Whitmore, J. M. Smoak, K. V. Kolasa, E. A Goddard, and R. Bindler. 2008. Arsenic contamination of lake sediments in Florida: evidence of herbicide mobility from watershed soils. J. Paleolimno. 40:869-884.

Wild, A. 1993. Soils and the Environment: An Introduction. Cambridge University Press, New York, New York. Pp. 255-261.

Williams, W. M., Holden, P. W., Parson, and M. N. Lorber. 1988. Pesticides in groundwater database, 1988 interim report. U.S. Environmental Protection Agency Office of Pesticide Programs, Washington, DC.

Winton, K. and J. B. Weber. 1996. A review of field lysimeter studies to describe the environmental fate of pesticides. Weed Technol. 10:202-209.

Wolcott, A. R. 1970. Retention of pesticides by organic materials in soils. *In* Pesticides in the Soil: Ecology, Degradation, and Movement. International Symposium on Pesticides in Soil. Lansing, MI: Michigan State University. Pp. 128–138.

Yamamoto, T. V. U. Ultra Jr., S. Tanaka, K. Sakurai, and K. Iwasaki. 2008. Effects of methyl bromide fumigation, chloropicrin fumigation and steam sterilization on soil nitrogen dynamics and microbial properties in a pot culture experiment. Soil Sci. and Plant Nut. 54:886-894.

Zheng, W., S. R. Yates, and S. H. Papiernik. 2008. Transformation kinetics and mechanism of the sulfonylurea herbicides pyrazosulfuron ethyl and halosulfuron methyl in aqueous solutions. J. Agric. Food Chem. 56:7367-7372.

Table 1. Soil physical and chemical properties of treated bare ground or established turf field lysimeters in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult) by depth.†

Soil depth (cm)	Organic matter ‡ (%)	CEC ‡ (meq/100 g soil)	pH ‡	Sand ‡ (%)	Silt ‡ (%)	Clay ‡ (%)
Bareground						
0-2	1.3	3.3	6.5	89	10	1
2-4	1.4	3.5	6.7	87	8	5
4-8	1.7	3.2	6.5	93	6	1
8-15	1.4	3.4	6.2	91	8	1
15-30	1.4	2.2	5.8	87	8	5
30-45	0.6	1.6	5.7	89	6	5
45-60	0.4	1.8	5.7	83	6	11
60-91	0.3	1.6	5.7	89	4	7
Established turf						
0-2	4.3	5.6	6.5	87	8	5
2-4	2.5	3.6	6.4	93	6	1
4-8	2.1	3.3	6.5	87	10	3
8-15	1.9	3	6.2	85	10	5
15-30	1.1	2.6	6.1	91	2	7
30-45	0.5	1.8	6.2	85	10	5
45-60	0.3	2.3	5.6	83	6	11
60-91	0.2	1.8	5.7	89	6	5

Table 1. (continued)

† Montgomery County Geological Soil Survey.

‡ A&L Eastern Laboratories, Inc., Richmond, VA, 23237.

Table 2. Herbicide physicochemical properties and biological properties.

	Herbicide				
Property	Atrazine	Mesotrione	MSMA	Pendimethalin	Sulfentrazone
Chemical family †	chlorotriazine	triketone	organic arsenical	dinitroanaline	aryl triazinone
Application rate (kg ai ha^{-1})	2.2	0.6	4.5	3.4	0.4
Molecular weight (g mol^{-1}) †	215.7	339.3	162	281.3	387.2
Vapor pressure (Pa) †	3.9×10^{-5} (25°C)	5.7×10^{-6}	1.3×10^{-3} (20°C)	1.3×10^{-3} (25°C)	1.1×10^{-7} (25°C)
Water solubility (mg L^{-1}) †	33 (pH 7)	15,000 (pH 6.9)	1,040,000	0.3	780 (pH 7)
K_d (mL g^{-1}) †	1	0.1 - 5	17.5	49 - 1,800	< 1
K_{oc} (mL g^{-1}) †	100	14 - 390	1,615	17,200	43
Field half-life (days) †	60	5 to 15	180	44	121 to 302
Ionizability (pK_a) †	1.7	3.1	4.1, 9.0	nonionizable	6.6
Pesticide leaching potential index ‡	56 (medium)	39 (low)	35 (low)	20 (very low)	54 (medium)

Table 2. (continued)

† Senseman, 2007.

‡ Pesticide leaching potential index. North Carolina Agricultural Chemicals Manual, 2010.

Table 3. Effect of application season and system on atrazine concentration from field-treated lysimeters 120 days after treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Atrazine	Summer		Winter	
Depth (cm) or vegetation	Bareground	Active turf	Bareground	Dormant turf
	($\mu g\ kg^{-1}$) ‡			
Above ground vegetation	-	1.0	-	229.7
0 - 2	3.1	1.9	113.5	336.6
2 - 4	1.6	1.4	87.5	192.6
4 - 8	1.1	1.2	80.9	44.5
8 - 15	0.2	1.1	89.6	30.5
15 - 30	0.0	1.0	33.5	10.5
30 - 45	0.0	0.0	8.1	2.3
45 - 60	0.0	0.0	0.0	0.0
60 - 90	NA §	NA	0.0	0.0
LSD (P = 0.05) ¶ #	2.1	1.4	56.5	112.0
Lysimeter total ($\mu g\ kg^{-1}$)	6.0	7.6	413.2	846.8
Initial (day 0) ($\mu g\ kg^{-1}$)	6749.0	6749.0	6749.0	6749.0
Percent of initial	0.1	0.1	6.1	12.5
Surface soil (0 - 4 cm) ($\mu g\ kg^{-1}$)	4.7	3.3	201.0	529.3
Percent of total in surface soil	78.0	43.7	48.6	62.5
Surface soil (0 - 4 cm) or vegetation ($\mu g\ kg^{-1}$)	-	4.4	-	759.0
Percent of total in surface soil or vegetation	-	57.1	-	89.6
Subsurface soil (4 - 90 cm) ($\mu g\ kg^{-1}$)	1.3	3.3	212.2	87.8
Percent of total in subsurface soil	22.0	42.9	51.4	10.4

† Montgomery County Geological Soil Survey.

‡ Atrazine concentration reported based on mean of two replications.

§ NA = Not analyzed.

Table 3. (continued)

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

Table 4. Effect of application season and system on mesotrione concentration from field-treated lysimeters 60 days after initial treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Mesotrione	Summer		Winter	
Depth (cm) or vegetation	Bareground	Active turf	Bareground	Dormant turf
	($\mu g\ kg^{-1}$) ‡			
Above ground vegetation	-	1.8	-	34.7
0 - 2	6.3	3.6	26.9	34.2
2 - 4	6.7	2.8	17.4	12.7
4 - 8	14.9	1.2	9.2	4.3
8 - 15	13.6	2.2	10.0	3.5
15 - 30	3.9	1.2	3.7	1.5
30 - 45	0.0	0.0	0.0	0.0
45 - 60	0.0	0.0	0.0	0.0
60 - 90	NA §	NA	NA	NA
LSD ($P = 0.05$) ¶ #	9.6	2.4	14.4	18.1
Lysimeter total ($\mu g\ kg^{-1}$)	45.5	12.9	67.2	90.9
Initial (day 0) ($\mu g\ kg^{-1}$)	1567.0	1567.0	1567.0	1567.0
Percent of initial	2.9	0.8	4.3	5.8
Surface soil (0 - 4 cm) ($\mu g\ kg^{-1}$)	13.1	6.4	44.4	46.9
Percent of total in surface soil	28.7	49.7	66.0	51.6
Surface soil (0 - 4 cm) or vegetation ($\mu g\ kg^{-1}$)	-	8.2	-	81.6
Percent of total in surface soil or vegetation	-	64.1	-	89.7
Subsurface soil (4 - 90 cm) ($\mu g\ kg^{-1}$)	32.4	4.6	22.8	9.3
Percent of total in subsurface soil	71.3	35.9	34.0	10.3

† Montgomery County Geological Soil Survey.

‡ Mesotrione concentration reported based on mean of two replications.

§ NA = Not analyzed.

Table 4. (continued)

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

Table 5. Effect of application season and system on mesotrione concentration from field-treated lysimeters 120 days after initial treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Mesotrione	Summer		Winter	
Depth (cm) or vegetation	Bareground	Active turf	Bareground	Dormant turf
	($\mu g\ kg^{-1}$) ‡			
Above ground vegetation	-	1.1	-	15.2
0 - 2	1.7	4.0	10.6	27.8
2 - 4	2.5	1.1	14.3	11.2
4 - 8	3.1	1.1	10.8	5.2
8 - 15	3.1	0.8	6.4	5.7
15 - 30	1.6	0.6	2.3	3.1
30 - 45	0.0	0.0	0.0	0.0
45 - 60	0.0	0.0	0.0	0.0
60 - 90	NA §	NA	NA	NA
LSD ($P = 0.05$) ¶ #	1.6	1.9	10.0	17.1
Lysimeter total ($\mu g\ kg^{-1}$)	11.9	8.7	44.3	68.3
Initial (day 0) ($\mu g\ kg^{-1}$)	1567.0	1567.0	1567.0	1567.0
Percent of initial	0.8	0.6	2.8	4.4
Surface soil (0 - 4 cm) ($\mu g\ kg^{-1}$)	4.2	5.1	24.9	39.1
Percent of total in surface soil	35.2	58.6	56.1	57.2
Surface soil (0 - 4 cm) or vegetation ($\mu g\ kg^{-1}$)	-	6.2	-	54.3
Percent of total in surface soil or vegetation	-	71.5	-	79.5
Subsurface soil (4 - 90 cm) ($\mu g\ kg^{-1}$)	7.7	2.5	19.5	14.0
Percent of total in subsurface soil	64.8	28.5	43.9	20.5

† Montgomery County Geological Soil Survey.

‡ Mesotrione concentration reported based on mean of two replications.

§ NA = Not analyzed.

Table 5. (continued)

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

Table 6. Effect of monosodium methylarsonate (MSMA), application season and system on total arsenic (As) concentration from field-treated lysimeters 120 days after initial treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

MSMA	Background As		Summer		Winter	
Depth (cm) or vegetation	Bareground	Turf	Bareground	Active turf	Bareground	Dormant turf
	(mg As kg^{-1}) ‡		Elevated As (mg As kg^{-1}) §			
Above ground vegetation	-	0.667	-	3.260	-	3.443
0 - 2	0.609	0.690	0.698	1.583	1.398	2.515
2 - 4	0.559	0.585	0.670	0.895	0.783	0.810
4 - 8	0.635	0.838	0.568	0.558	0.448	0.115
8 - 15	0.536	0.584	0.415	0.560	0.303	0.268
15 - 30	0.595	0.782	0.000	0.003	0.170	0.000
30 - 45	0.754	0.758	0.000	0.000	0.030	0.000
45 - 60	0.759	0.756	0.000	0.000	0.000	0.000
60 - 90	0.768	0.760	0.000	0.000	0.000	0.000
LSD (P = 0.05) ¶ #	-	-	0.230	0.982	0.494	0.624
Lysimeter total (mg kg^{-1})	5.2	6.4	2.4	6.9	3.1	7.2
Initial (day 0) (mg kg^{-1})	-	-	3.7	3.7	3.7	3.7
Percent of initial	-	-	63.8	186.3	85.0	194.2
Surface soil (0 - 4 cm) (mg kg^{-1})	1.2	1.3	1.4	2.5	2.2	3.3
Percent of total in surface soil	22.4	19.8	58.2	36.1	69.6	46.5
Surface soil (0 - 4 cm) or vegetation (mg kg^{-1})	-	1.9	-	5.7	-	6.8
Percent of total in surface soil or vegetation	-	30.2	-	83.7	-	94.7
Subsurface soil (4 - 90 cm) (mg kg^{-1})	4.0	4.5	1.0	1.1	1.0	0.4
Percent of total in subsurface soil	77.6	69.8	41.8	16.3	30.4	5.3

† Montgomery County Geological Soil Survey.

‡ Background As levels determined from samples collected June 2007.

§ Arsenic concentration reported based on mean of two replications after MSMA application less background As.

Table 6. (continued)

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

Table 7. Effect of application season and system on pendimethalin concentration from field-treated lysimeters 120 days after treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Pendimethalin	Summer		Winter	
Depth (cm) or vegetation	Bareground	Active turf	Bareground	Dormant turf
	($\mu g\ kg^{-1}$) ‡			
Above ground vegetation	-	172.9	-	2152.5
0 - 2	873.1	362.3	4014.6	2032.4
2 - 4	505.0	123.3	581.7	176.3
4 - 8	175.3	62.4	120.8	73.9
8 - 15	34.6	57.1	57.4	27.9
15 - 30	3.7	3.2	15.6	3.9
30 - 45	0.0	0.0	0.0	0.0
45 - 60	0.0	0.0	0.0	0.0
60 - 90	NA §	NA	NA	NA
LSD (P = 0.05) ¶ #	437.8	175.7	781.6	689.2
Lysimeter total ($\mu g\ kg^{-1}$)	1591.7	781.1	4790.1	4466.9
Initial (day 0) ($\mu g\ kg^{-1}$)	10385.0	10385.0	10385.0	10385.0
Percent of initial	15.3	7.5	46.1	43.0
Surface soil (0 - 4 cm) ($\mu g\ kg^{-1}$)	1378.1	485.6	4596.3	2208.7
Percent of total in surface soil	86.6	62.2	96.0	49.4
Surface soil (0 - 4 cm) or vegetation ($\mu g\ kg^{-1}$)	-	658.5	-	4361.2
Percent of total in surface soil or vegetation	-	84.3	-	97.6
Subsurface soil (4 - 90 cm) ($\mu g\ kg^{-1}$)	213.6	122.6	193.8	105.7
Percent of total in subsurface soil	13.4	15.7	4.0	2.4

† Montgomery County Geological Soil Survey.

‡ Mesotrione concentration reported based on mean of two replications.

Table 7. (continued)

§ NA = Not analyzed.

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

Table 8. Effect of application season and system on sulfentrazone concentration from field-treated lysimeters 120 days after treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Sulfentrazone	Summer		Winter	
Depth (cm) or vegetation	Bareground	Active turf	Bareground	Dormant turf
	(μg kg^{-1}) ‡			
Above ground vegetation	-	2.4	-	84.7
0 - 2	7.8	5.6	31.4	118.6
2 - 4	12.7	4.5	42.9	69.1
4 - 8	21.5	3.6	39.8	18.7
8 - 15	42.4	6.5	42.0	11.9
15 - 30	20.0	5.0	16.2	4.0
30 - 45	1.6	0.3	2.6	0.3
45 - 60	1.3	0.0	1.0	0.0
60 - 90	0.0	0.0	0.0	0.0
LSD (P = 0.05) § ¶	11.0	3.0	32.3	22.7
Lysimeter total (μg kg^{-1})	107.3	28.0	175.9	307.2
Initial (day 0) (μg kg^{-1})	1436.0	1436.0	1436.0	1436.0
Percent of initial	7.5	2.0	12.3	21.4
Surface soil (0 - 4 cm) (μg kg^{-1})	20.5	10.1	74.3	187.6
Percent of total in surface soil	19.1	36.0	42.2	61.1
Surface soil (0 - 4 cm) or vegetation (μg kg^{-1})	-	12.5	-	272.3
Percent of total in surface soil or vegetation	-	44.7	-	88.7
Subsurface soil (4 - 90 cm) (μg kg^{-1})	86.8	15.5	101.6	34.8
Percent of total in subsurface soil	80.9	55.3	57.8	11.3

† Montgomery County Geological Soil Survey.

‡ Mesotrione concentration reported based on mean of two replications.

§ LSD = Least significant difference.

Table 8. (continued)

¶ Based on Fisher's Protected LSD.

Table 9. Effect of application season on herbicide concentration from field-treated lysimeters after treatment in a Candor sand (sandy, siliceous, thermic grossarenic kandiudult). †

Season	Atrazine	Mesotrione (60d)	Mesotrione (120d)	Pendimethalin	Sulfentrazone	MSMA
	———	———	(µg analyte kg^{-1}) ‡	———	———	(mg As § kg^{-1}) ‡
Summer	0.9	3.9	1.4	157.9	9.0	0.5
Winter	76.4	10.5	7.5	617.1	32.6	0.6
LSD (P = 0.05) ¶ #	23.7	3.8	3.0	236.8	9.1	NS

† Montgomery County Geological Soil Survey.

‡ Herbicide or element concentration reported based on mean of two replications.

§ As = arsenic

¶ LSD = Least significant difference.

Based on Fisher's Protected LSD.

1. Weigh 10 g soil, place in 175 mL conical centrifuge bottle
2. Add 50 mL acetone:n-hexane (1:1)
3. Shake 30 min on orbital shaker (240 rpm)
4. Centrifuge 10 min (4000 rpm), decant
5. Repeat steps 2-4, combine supernatant
6. Bring up to 100 mL final volume with acetone:n-hexane (1:1)
7. Take 1 mL aliquot supernatant
8. Evaporate to dryness with nitrogen evaporator
9. Redissolve in 4 mL methanol:water (1:1)
10. Filter through 0.45 μm syringe filter
11. Vial sample, analyze by LC/MS-MS

Figure 1. Atrazine extraction schematic.

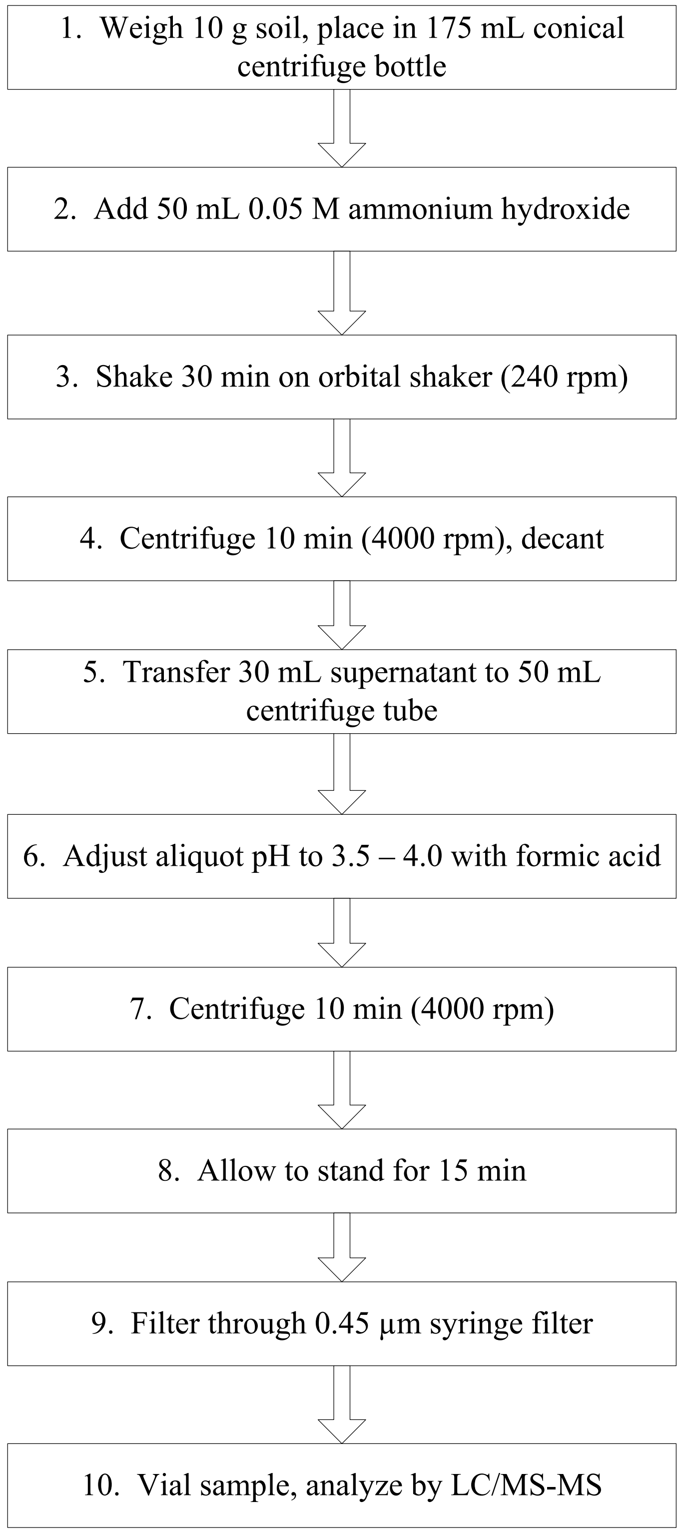

Figure 2. Mesotrione extraction schematic.

Figure 3. Total arsenic determination schematic.

1. Weigh 2 g soil, place in digestion tube
2. Add 15 mL deionized water:nitric acid (1:1), allow to stand for 16 h
3. Heat capped tubes to 95° C for 15 min, allow tubes to cool
4. Add 5 mL 15.8M nitric acid, vortex, heat to 95° C for 30 min, allow to cool
5. Repeat step 4
6. Heat uncapped tubes to 95° C for 2 hours, allow to cool
7. Add 3 mL deionized water and 2 mL 30% hydrogen peroxide, heat to 95° C until effervescence subsides
8. Add 4 mL 30% hydrogen peroxide (1 mL incrementally to allow effervescence)
9. Vortex, heat to 95° C for 2 h, allow to cool

10. Add 10 mL 12.1 M hydrochloric acid, heat to 95° C for 15 min, allow to cool

↓

11. Filter through Whatman #41 filter paper, bring to 50 mL final volume with deionized water

↓

12. Dilute digestate 1:5, vial, analyze with MS

1. Weigh 10 g soil, place in 175 mL conical centrifuge bottle

↓

2. Add 25 mL deionized water, swirl for 15 s

↓

3. Add 75 mL acidic methanol (2%)

↓

4. Shake 1 h on orbital shaker (240 rpm)

↓

5. Centrifuge 10 min (4000 rpm), decant

↓

6. Filter through 0.45 µm syringe filter

↓

7. Vial sample, analyze by LC/MS-MS

Figure 4. Pendimethalin extraction schematic.

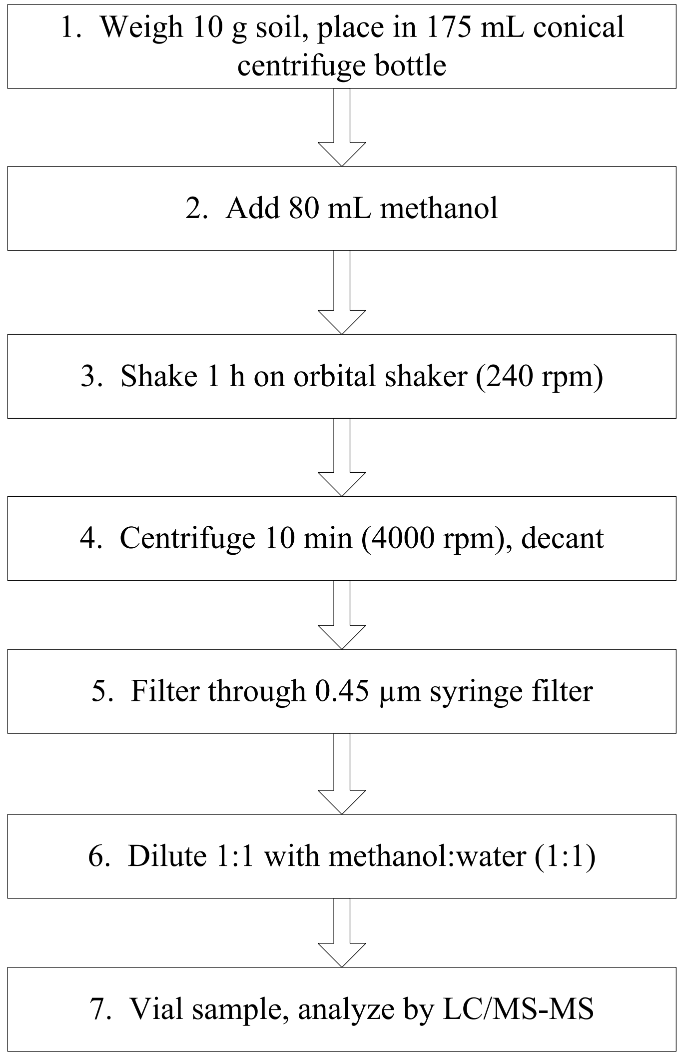

Figure 5. Sulfentrazone extraction schematic.

APPENDIX

Table A1. Daily rainfall, Jackson Springs, NC, summer 2007.[†]

	Month				
Day	May	June	July	August	September
	cm				
1		-	0.05	-	-
2		-	-	-	-
3		3.10	-	-	-
4		0.25	-	-	-
5		-	-	-	-
6		-	-	-	-
7		-	-	-	-
8		-	0.05	-	-
9		-	-	-	-
10		-	0.18	-	-
11		-	-	-	-
12		0.15	2.87	-	-
13		-	-	-	-
14		0.48	-	-	-
15		0.84	-	-	3.61
16		0.13	1.45	-	-
17		1.32	-	-	-
18		-	0.64	-	-
19		-	-	-	-
20		0.05	-	-	-
21	-	0.08	-	-	0.64
22	-	-	-	0.08	-
23	0.13	-	-	0.53	
24	-	-	-	-	
25	-	0.48	-	-	
26	-	-	-	-	
27	-	0.46	0.81	0.25	
28	-	-	-	-	
29	-	-	-	-	
30	-	1.19	-	0.05	
31	-	N/A	0.33	0.13	
Sum	0.13	8.53	6.38	1.04	4.24

[†] Rainfall recorded onsite by North Carolina Agriculture Research Service.

Table A2. Daily rainfall, Jackson Springs, NC, Winter 2007/2008.[†]

Day	Month				
	November	December	January	February	March
	cm				
1		-	-	1.02	-
2		-	-	0.74	-
3		0.13	-	-	-
4		-	-	-	-
5		-	-	-	2.08
6		-	-	0.05	-
7		-	-	-	-
8		-	-	-	2.34
9		-	-	-	-
10		-	-	-	-
11		-	0.10	-	-
12	-	-	0.05	-	-
13	-	-	-	1.12	
14	-	-	-	0.36	
15	0.13	-	-	-	
16	0.36	3.10	-	-	
17	-	0.05	0.20	-	
18	-	-	2.03	2.24	
19	-	-	0.48	-	
20	-	-	-	-	
21	-	0.53	-	-	
22	-	0.05	-	1.32	
23	-	-	1.32	0.28	
24	-	0.51	-	-	
25	-	-	-	0.03	
26	0.48	3.30	-	-	
27	0.41	1.68	-	1.14	
28	-	-	-	-	
29	-	0.38	-	-	
30	-	1.50	0.33	N/A	
31	N/A	3.20	-	N/A	
Sum	1.37	14.43	4.52	8.28	4.42

[†] Rainfall recorded onsite by North Carolina Agriculture Research Service.

Table A3. Daily rainfall, Jackson Springs, NC, summer 2008.[†]

Day	June	July	August	September	October
			Month		
			cm		
1		-	0.43	-	0.13
2	0.58	-	-	-	-
3	-	-	1.93	-	-
4	-	-	-	-	
5	-	0.03	-	-	
6	-	0.36	-	7.34	
7	-	2.59	-	0.08	
8	-	-	0.30	-	
9	-	4.50	-	-	
10	-	1.70	-	0.33	
11	-	0.25	2.16	1.91	
12	0.18	-	-	-	
13	-	-	0.41	-	
14	-	-	4.50	-	
15	2.24	0.15	-	-	
16	-	-	0.56	-	
17	-	-	0.13	1.78	
18	-	-	1.19	-	
19	-	0.56	-	-	
20	-	-	-	-	
21	-	-	-	-	
22	1.04	-	-	-	
23	-	-	-	-	
24	-	3.10	-	-	
25	-	-	-	-	
26	-	-	2.34	2.16	
27	-	-	6.73	1.40	
28	-	-	0.03	-	
29	0.05	-	-	-	
30	-	-	1.52	-	
31	N/A	-	0.05	N/A	
Sum	4.09	13.23	22.28	14.99	0.13

† Rainfall recorded onsite by North Carolina Agriculture Research Service.

Table A4. Daily rainfall, Jackson Springs, NC, Winter 2008/2009.[†]

Day	November	December	January	February	March
	cm				
1		1.50	-	-	3.40
2		-	-	-	3.35
3		-	-	0.74	-
4		-	1.14	0.15	-
5	0.89	-	-	-	-
6	-	-	1.07	-	-
7	-	-	0.43	-	
8	-	-	0.56	-	
9	-	-	-	-	
10	-	0.23	-	-	
11	-	3.05	0.56	-	
12	-	2.03	-	0.48	
13	-	-	-	-	
14	0.69	-	-	-	
15	5.72	-	-	0.13	
16	-	-	-	0.13	
17	-	0.05	-	-	
18	-	-	-	0.25	
19	-	0.08	0.25	2.41	
20	-	-	0.46	-	
21	-	1.52	0.15	-	
22	-	-	-	-	
23	-	-	-	-	
24	-	-	-	-	
25	0.74	-	-	-	
26	-	-	-	-	
27	-	0.30	-	-	
28	-	-	-	0.69	
29	-	0.13	0.56	N/A	
30	2.01	-	-	N/A	
31	N/A	-	-	N/A	
Sum	10.03	8.89	5.18	4.98	6.76

[†] Rainfall recorded onsite by North Carolina Agriculture Research Service.

PURPLE NUTSEDGE (*CYPERUS ROTUNDUS*) AND FALSE-GREEN KYLLINGA (*KYLLINGA GRACILLIMA*) CONTROL IN BERMUDAGRASS TURF.

Formatted for Weed Technology

Travis W. Gannon, Fred H. Yelverton and Lane P. Tredway*

Experiments were conducted during 2007 and 2008 to evaluate various herbicide treatment regimes for postemergent purple nutsedge and false-green kyllinga control. Evaluated treatments did not cause objectionable bermudagrass injury at any time. Results were variable across years, likely due to reduced rainfall in 2007 causing reduced purple nutsedge and false-green kyllinga growth. In 2007, averaged across herbicide rate and number of applications, sulfosulfuron provided greater purple nutsedge control than trifloxysulfuron. Sulfosulfuron and trifloxysulfuron provided similar levels of control in 2008, although both were less effective than in 2007. In 2007, sulfosulfuron and trifloxysulfuron provided excellent false-green kyllinga control, while trifloxysulfuron provided greater control compared to sulfosulfuron in 2008. Sulfentrazone provided < 30

Received for publication __________ and in approved form __________.

* First and second authors: Research Associate and Professor, Department of Crop Science, North Carolina State University, Raleigh, NC 27695; Third author: Associate Professor, Department of Plant Pathology, North Carolina State University, Campus Box 7616, Raleigh, NC 27695. Corresponding author's E-mail: travis_gannon@ncsu.edu.

and 60% purple nutsedge and false-green kyllinga control, respectively. The results also indicate that a sequential application applied 6 WAIT provides the highest level of purple nutsedge and false-green kyllinga control with evaluated herbicides. Tank-mix partners to enhance purple nutsedge control with sulfentrazone provided inconsistent results. These data confirm that sulfosulfuron or trifloxysulfuron offer acceptable postemergent perennial sedge control in tolerant warm-season turfgrasses.

Nomenclature: halosulfuron; sulfentrazone; sulfosulfuron; trifloxysulfuron; false-green kyllinga, *Kyllinga gracillima* L.; purple nutsedge, *Cyperus rotundus* L.; bermudagrass, *Cynodon* spp.

Key words: Herbicide efficacy, sequential applications, sequential application timing, tank-mix partner.

Purple nutsedge (*Cyperus rotundus* L.) and false-green kyllinga (*Kyllinga gracillima* Miq.) are common perennial sedge species (Cyperaceae) in turfgrass systems. Purple nutsedge and most kyllinga spp. are C_4 plants (Bryson and Carter 2008; Lin et al. 1993) which possess specialized leaf anatomy allowing increased growth and efficiency under high light and temperature regimes (Hattersley 1983; Lin et al. 1993; Teeri and Stowe 1976). Purple nutsedge and false-green kyllinga thrive in moist soil conditions (Bendixen and Nandihalli 1987; McElroy et al. 2005b) and tolerate routine mowing. Summerlin et al. (2000) concluded that routine mowing at golf course fairway mowing height (1.3 cm) suppresses purple nutsedge growth, although additional control methods are required to provide acceptable levels of control. In contrast, false-green kyllinga is able to withstand frequent mowing at heights as low as 1.3 cm (Bryson et al. 1997; Summerlin et al. 2000). Observations of green kyllinga (*Kyllinga brevifolia* Rottb.) and false-green kyllinga under golf course putting green mowing height and frequency indicate these species may tolerate any mowing regime in a managed turfgrass system (F. H. Yelverton, personal observation).

Native to India, purple nutsedge is a rapidly spreading perennial with three-ranked basal leaves usually shorter than the flowering stem (Chase and Appleby 1979; McCarty et al. 2008). Although not as widely distributed as other *Cyperus* species, purple nutsedge was described as the world's worst weed because it is a serious competitor with more crops in more countries than any other weed (Holm et al. 1977). The geographical distribution of purple nutsedge appears to have increased over the last 40 years. According to 'Weed Identification Guide' published in 1970, purple nutsedge was distributed mostly in the southeastern United States north to Virginia, south to Florida, and west to Texas and Arkansas and also in California and Arizona (Elmore 1990); however, in 1992, that distribution was reported to also include West Virginia and Kentucky (Murphy et al. 1992). Further, by 2009, purple nutsedge distribution had expanded north to include Pennsylvania and New Jersey (Bryson and Carter 2008). The geographic distribution of purple nutsedge is restricted by temperature and moisture (Bendixen and Nandihalli 1987). Yellow nutsedge (*Cyperus esculentus* L.) has a greater geographic distribution and is able to survive in cooler climates (McCarty et al. 2008). This is likely due to its ability to increase tuber starch, sugar and lipid contents in response to temperature, unlike purple nutsedge (Bendixen and Nandihalli 1987).

Purple nutsedge spreads by basal bulbs, viable seed and tuber chains which are connected by slender rhizomes (Murphy et al. 1992); however, Stoller and Sweet (1987) concluded seed are not important in purple nutsedge propagation. Purple nutsedge may be differentiated from yellow nutsedge by inflorescence color, absence of tuber chains and leaf tip shape (Bryson and DeFelice 2009). Although yellow nutsedge has been cultivated for its edible tubers in southern Europe and Africa, purple nutsedge tubers are not used for food and have an undesirable bitter taste (Bryson and DeFelice 2009; Wills 1987).

False-green kyllinga is an aromatic rhizomatous mat-forming perennial native to Asia (Bryson et al. 1997). The reported geographic distribution of false-green kyllinga varies, but it is unclear if this is due to spread over time or misidentification. Bryson et al. (1997) reported the species had spread to include nine additional states in the previous two decades. McCarty et al. (2008) reported false-green kyllinga distribution in the southeastern United States from Pennsylvania south to Florida, west to Texas and also in California; however, Bryson et al. (1997) and USDA (2010b) did not report false-green kyllinga in Florida, Louisiana, Texas or California. Bryson et al. (1997) and USDA (2010b) also reported false-green kyllinga as far north as Connecticut.

False-green kyllinga is very similar vegetatively to green kyllinga and can only be differentiated by seed morphology or flower timing (Bryson et al. 1997). Scale keels of green and false-green kyllinga seed are toothed (denticulate) and smooth, respectively (Bryson et al. 1997). False-green kyllinga fruit development is photoperiod dependent, occurring in late summer (August) until frost, whereas green kyllinga fruits during most summer months (Bryson et al. 1997; McCarty et al. 2008). False-green kyllinga may be propagated by seed or rhizomes (McCarty et al. 2008) and has been reported to spread as contaminants of turfgrass sod and sprigs (Bryson et al. 1997).

Changes in herbicide programs have contributed to an increase in *Kyllinga* and *Cyperus* incidence in turfgrass environments (Yelverton 1996). Traditionally, postemergent monosodium salt of methylarsonic acid (MSMA) applications were used to control summer annual grasses, including crabgrass (*Digitaria* spp.) and goosegrass (*Eleusine indica*), and also controlled nutsedge and kyllinga species. Today, turfgrass managers rely less on postemergent herbicides in favor of preemergent herbicides that do not control *Kyllinga* and *Cyperus* species from perennial structures.

Previous research has evaluated various herbicides and combinations for purple nutsedge and false-green kyllinga control. Selective herbicide options are available in most turfgrasses, although each species is difficult to control long-term as they possess vegetative structures capable of overwintering in select climates. Blum et al. (2000) reported minimal purple nutsedge control ($\leq$ 25%) with single sulfentrazone applications (0.42 kg/ha) in established turfgrass; however, Grichar et al. (2003) reported greater than 75% control in field crops. Sulfentrazone provides > 75% false-green kyllinga control, whereas repeat trifloxysulfuron applications provide > 85% false-green kyllinga control in turfgrass systems (McElroy et al. 2005a). Sulfosulfuron (Baumann et al. 2004; Brecke et al. 2007; Eizenberg et al. 2003; Harrell et al. 2009; Hubbard et al. 2007) and trifloxysulfuron (Brecke et al. 2004; Burke et al. 2008; Hubbard et al. 2007) have been reported to provide acceptable purple nutsedge control. However, research comparing sulfentrazone, sulfosulfuron, and trifloxysulfuron for perennial sedge control in turfgrass environments is not currently available.

The objectives of this research were to evaluate: 1) single versus sequential sulfentrazone, sulfosulfuron and trifloxysulfuron applications for purple nutsedge and false-green kyllinga control, 2) timing of sequential sulfentrazone, sulfosulfuron and trifloxysulfuron application for purple nutsedge and false-green kyllinga control, and 3) sulfentrazone tank-mix partners to enhance purple nutsedge control.

Materials and Methods

Herbicide, Application Rate and Sequential Application. Experiments were initiated to investigate the effect of herbicide, application rate and one versus two applications for purple nutsedge and false-green kyllinga control. Purple nutsedge control experiments were conducted at Plymouth Country Club in Plymouth, NC in 2007 and New Bern Country Club in Trent Woods, NC in 2008. Soil type at Plymouth Country Club was a Wahee fine sandy loam (fine, mixed, semiactive thermic Aeric Endoaquults) with 1.3% humic matter (HM) and pH 5.5 (USDA 2010b). Soil type at New Bern Country Club was Tarboro sand (mixed, thermic Typic Udipsamments) with 1.6% HM and pH 5.9 (USDA 2010b). False-green kyllinga control experiments were conducted at Hidden Valley Golf Club near Fuquay-Varina, NC in 2007 and The Emerald Golf Club in New Bern, NC in 2008. Soil type at Hidden Valley Golf Club was Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) with 1.7% HM and pH 4.9 (USDA 2010b). Soil type at The Emerald Golf Club was Tarboro sand with 1.4% HM and pH 5.9 (USDA 2010b). HM was determined by the NaOH/DTPA-alcohol extraction method at the North Carolina State Department of Agriculture Plant and Soil Laboratory in Raleigh, NC (Mehlich 1984). Experiments were initiated in natural infestations of purple nutsedge or false-green kyllinga. Experimental areas were comprised of common bermudagrass (*Cynodon dactylon* L. Pers.) and received supplemental irrigation and fertilization. Purple nutsedge control experiments were conducted in a golf course fairway mown at 1.9 cm three to four times per week. False-green kyllinga experiments were conducted in a golf course rough mown at 3.8 cm two to three times per week. Experiments utilized a randomized complete block design with a factorial arrangement of treatments and each experiment included four replications with plot size ranging from 1.9 to 2.2 m^2.

Three herbicides (sulfentrazone[1], sulfosulfuron[2] or trifloxysulfuron[3]), three application rates (low, medium or high) and one versus two applications were evaluated. A nontreated was included in each experiment. Single treatments were applied at experiment initiation only, whereas treatments evaluating two applications were applied at experiment initiation and six weeks after initial treatment (WAIT). Herbicide rates were 0.14, 0.28, or 0.42 kg ai/ha sulfentrazone, 0.033, 0.049, or 0.066 kg/ha sulfosulfuron or 0.015, 0.022, or 0.029 kg/ha trifloxysulfuron. Evaluated rate structure was based on current label recommendations and restrictions. A nonionic surfactant[4] was included with trifloxysulfuron and sulfosulfuron (0.25% vol/vol). Herbicide applications were made with a hand-held CO_2-propelled research plot sprayer calibrated to deliver 304 L/ha with four 8002XR flat fan nozzles[5] on 25 cm spacing at 193 kPa. Experiments were initiated mid- to late-June.

Data collected included purple nutsedge or false-green kyllinga shoot density and visual estimates of control. Control was visually estimated 4, 8 and 12 WAIT utilizing a 0 (no visible injury) to 100 % (complete plant death) scale. Shoot density was recorded 12 WAIT as the number of emerged shoots in two randomly selected areas (0.07 and 0.01 m^2, respectively, for purple nutsedge and false-green kyllinga) in each plot. Percent shoot number reduction, relative to the nontreated, was calculated by:

$$(((\text{Nontreated} - \text{treated})/\text{nontreated}) \times 100) \quad [1]$$

Purple nutsedge tubers and false-green kyllinga rhizomes were also collected 12 WAIT to determine viability. False-green kyllinga rhizomes were harvested by removing soil cores using a standard golf cup cutter (10.8 cm diameter by 7.6 cm deep) and rhizomes were removed from the soil. Purple nutsedge tubers were harvested similarly except cores were 20.3 cm deep. Stoller and Sweet (1987) reported most purple nutsedge tubers were located within 15 cm of the soil surface. Five purple nutsedge tubers or false-green kyllinga rhizomes were immediately planted 0.6 to 1.3 cm deep in growing medium[6]. Flats were placed in a greenhouse with day/night temperatures of 31/20C and were irrigated from overhead three times per day. Lighting was supplemented (350 $\mu mol/m^2/s$) with metal halide lamps (1000 watts) to simulate 16 h day length. Tubers and rhizomes were grown for one month and were visually inspected for emergence. Emerged vegetative structures were deemed viable while nonemerged were considered to be nonviable and percent tuber or rhizome viability was calculated.

Significant main effects and interactions were detected among species; therefore, purple nutsedge and false-green kyllinga data were analyzed separately. Data were arcsine square root transformed to increase homogeneity of variance (Zar 1999), subjected to ANOVA (P = 0.05), and means were separated according to Fisher's Protected LSD using SAS[7]. Nontransformed means are presented for clarity with statistical interpretation based on transformed data.

Herbicide, Sequential Application Timing and Herbicide Rate. Experiments were initiated to investigate the effect of herbicide, sequential application timing and herbicide rate for purple nutsedge and false-green kyllinga control. Experiment location, design, application and data collection were identical to those described above.

Two herbicides (sulfentrazone or trifloxysulfuron), three sequential application timings (4, 6 or 8 WAIT) and three herbicide application rates (low, medium or high) were evaluated. Herbicide rates were 0.14, 0.21, or 0.28 kg/ha sulfentrazone or 0.015, 0.022, or 0.029 kg/ha trifloxysulfuron. A nonionic surfactant was included with trifloxysulfuron (0.25% vol/vol). Single applications and a nontreated were included in each experiment for comparison.

Herbicide Tank-mix Partners with Sulfentrazone for Purple Nutsedge Control. Experiments were initiated to investigate the effect of herbicide tank-mix partners with sulfentrazone and application rates for purple nutsedge control. Experiment location, design, application and data collection were identical to those described above.

Herbicides included sulfentrazone alone or tank-mixed with halosulfuron[8], sulfosulfuron or trifloxysulfuron. Two rates of each herbicide were evaluated: 0.28 or 0.42 kg/ha sulfentrazone, 0.035 or 0.07 kg/ha halosulfuron, 0.033 or 0.066 kg/ha sulfosulfuron, or

0.015 or 0.029 kg/ha trifloxysulfuron. A nonionic surfactant (0.25% vol/vol) was included with all treatments except sulfentrazone alone. A nontreated was included in each experiment.

Results and Discussion

In evaluating main effects and interactions, significant ($P \leq 0.05$) year effects were observed for control, shoot number reduction and tuber viability; therefore, data were not pooled over years. Bermudagrass injury was never objectionable (< 20%) throughout experiments (data not shown).

Herbicide, Application Rate and Sequential Application. Reduced rainfall in 2007 likely reduced purple nutsedge and false-green kyllinga growth and resulted in overall improved control in 2007 compared to 2008. Cumulative rainfall during trial periods in 2007 was 18.0 cm (Plymouth, NC, purple nutsedge, Table A1) and 15.8 cm (Fuquay Varina, NC, false-green kyllinga, Table A2) while 29.1 cm was recorded during 2008 (New Bern, NC, false-green kyllinga and purple nutsedge, Table A3). At 12 WAIT in 2007, averaged across herbicide rate and number of applications, sulfosulfuron provided greater purple nutsedge control (92%) than trifloxysulfuron (77%) (Table 1). In 2008, sulfosulfuron and trifloxysulfuron only provided 50 and 58% control, respectively, likely due to increased rainfall in 2008 being more conducive to purple nutsedge growth. Purple nutsedge shoot number reduction followed similar trends as visual estimates of control. Previous research indicates one or two applications of sulfosulfuron (Baumann et al. 2004; Brecke et al. 2004; Brecke et al. 2007; Harrell et al. 2009; Hubbard et al. 2007; Marvin et al. 2009) or trifloxysulfuron (Brecke et al. 2004; Henry and Sladek 2008; Hubbard et al. 2007) provide acceptable purple nutsedge control. Purple nutsedge control with sulfosulfuron and trifloxysulfuron in these studies may have been lower due to inclusion of low application rates and single applications. Purple nutsedge is a difficult-to-control perennial species, and previous research shows that repeat applications are required for acceptable control in turfgrass environments (Brecke et al. 2007; Hubbard et al. 2007).

Regardless of year, sulfentrazone provided < 30% postemergent purple nutsedge control or shoot number reduction 12 WAIT, therefore sulfentrazone did not provide adequate control in our experiments (Table 1). Previous research has shown that sulfentrazone provides inconsistent purple nutsedge control. Single sulfentrazone applications (0.42 kg/ha) provided unacceptable (< 50%) purple nutsedge control (Blum et al. 2000; Kopec and Gilbert 2001; Marvin et al. 2009), however, repeat applications have been reported to provide acceptable control. Marvin et al. (2009) reported a sequential sulfentrazone application (0.28 kg/ha each) applied 28, 35, or 42 DAIT provided 70, 85, or 90% purple nutsedge control, respectively; however, evaluations were conducted in mid-August and may not have accounted for regrowth after sequential application. Similarly, Kopec and Gilbert (2001) reported 77% control with sulfentrazone (0.42 followed by (fb) 0.14 kg/ha) five WAIT, whereas Blum et al. (2000) reported < 50% control with 0.42 fb 0.42 kg/ha. Brecke et al. (2005) reported 86% control with 0.42 kg/ha applied preemergent fb 0.14 kg/ha applied early postemergent, indicating that purple nutsedge may be more susceptible during emergence or early postemergence; however, this research was completed in a disked field which may have influenced the results. Although organic matter content in Brecke et al. (2005) was similar to our research sites (~ 2%), since the area was disked prior to initiation, the area likely did not have an organic matter layer near the soil surface, possibly allowing sulfentrazone to distribute in the root zone and increasing root absorption. The thatch layer near the soil surface of an established turfgrass may readily adsorb sulfentrazone and reduce root absorption.

In our studies, no surfactant or adjuvant was included with sulfentrazone per label recommendations (Anonymous 2010b). Inclusion of a surfactant in previous research may explain greater purple nutsedge control, as Dayan et al. (1996) reported enhanced foliar absorption and yellow nutsedge control when a nonionic surfactant was included compared to sulfentrazone alone. Dayan et al. (1996) also concluded that a nonionic surfactant enhanced soybean (*Glycine max* (L.)) injury compared to sulfentrazone alone, likely due to increased uptake.

Purple nutsedge tubers harvested from nontreated plots were 100% viable (Table 1). Sulfosulfuron reduced purple nutsedge tuber viability the greatest (67 and 49%, respectively, in 2007 and 2008). Trifloxysulfuron also reduced tuber viability compared to the nontreated while tubers harvested from sulfentrazone-treated plots were ≥ 88% viable. Effectively reducing tuber population and viability are important for long-term purple nutsedge control (Johnson and Mullinix 1997; Molin et al. 1999). Previous research has demonstrated that sulfonylurea herbicides affect purple nutsedge tuber viability. Molin et al. (1999) concluded halosulfuron did not affect purple nutsedge tuber number or weight, although two applications reduced viability in field experiments. Brecke et al. (2005) reported a 55% reduction in purple nutsedge tuber number and 38% reduction in viability with two halosulfuron applications, and Nelson and Renner (2002) reported > 75% yellow nutsedge tuber number and weight reduction in greenhouse experiments with halosulfuron. Purple nutsedge control with herbicides may be suboptimal due to inconsistent or minimal translocation into tubers (Nesser et al. 1997). Previous research has reported minimal (≤ 4%) translocation into roots and tubers from foliar applications of sulfentrazone (Wehtje et al. 1997) or trifloxysulfuron (Troxler et al. 2003), indicating inadequate basipetal translocation may be a limiting factor in long-term purple nutsedge control.

Similar to purple nutsedge, false-green kyllinga control was numerically less in 2008, likely due to increased rainfall (Table 1). In 2007, trifloxysulfuron provided complete false-green kyllinga control and sulfosulfuron provided 91% control 12 WAIT. In 2008, trifloxysulfuron and sulfosulfuron provided 80% and 61% control, respectively. Shoot number reduction followed similar trends as visual estimates of control. These results concur with previous research that reported acceptable false-green kyllinga control with trifloxysulfuron (Breeden and McElroy 2005; McElroy et al. 2005a) or sulfosulfuron (Brosnan and Deputy 2008; Unruh and Brecke 2006).

Sulfentrazone did not provide acceptable false-green kyllinga control or shoot number reduction (≤ 58%). Similarly, McElroy et al. (2005a) reported 59 and 65% false-green kyllinga control with 0.42 and 0.56 kg/ha sulfentrazone, respectively, one year after treatment. These data indicate that adequate false-green kyllinga control may not be obtained each year in turfgrass environments and as previously mentioned may be affected by application rate, inclusion of a surfactant and rainfall, among other factors.

Similar to purple nutsedge, perennial structure viability must be reduced in order to achieve long-term false-green kyllinga control. False-green kyllinga rhizomes harvested from nontreated areas were 100% viable and evaluated herbicides reduced viability (Table 1). Sulfosulfuron and trifloxysulfuron reduced false-green kyllinga rhizome viability by 87 and 100%, respectively, in 2007 and 2008. Sulfentrazone reduced rhizome viability (40 and

21%, respectively in 2007 and 2008) compared to the nontreated. The reduction in false-green kyllinga rhizome viability with foliar-applied sulfosulfuron or trifloxysulfuron is likely due to significant translocation to this region. Although foliar-applied trifloxysulfuron is distributed mainly in the treated leaf and primary shoot of false-green kyllinga, appreciable trifloxysulfuron translocates to rhizomes and roots (McElroy et al. 2004).

Excluding purple nutsedge in 2007, medium and high herbicide rates provided greater purple nutsedge or false-green kyllinga control and shoot number reduction compared to low rates (Table 2). Although numerically greater, in most cases the highest evaluated rate did not increase false-green kyllinga or purple nutsedge control or shoot number reduction compared to the medium rate. In 2007, medium and high rates of evaluated herbicides provided 63 and 71% purple nutsedge control, respectively, while control was 14 – 19% less in 2008.

Similar trends were observed with false-green kyllinga, although control was greater in general (Table 2). False-green kyllinga control was 11 – 15% greater in 2007, with medium and high herbicide rates providing > 80% control. McElroy et al. (2005a) reported similar false-green kyllinga control with 0.42 or 0.56 kg/ha sulfentrazone providing 77 and 87% control, respectively. Increased herbicide rates tend to increase weed control, particularly with difficult-to-control species such as perennial sedges. It should be noted that the lowest evaluated rate in our study was lower than recommended for sedge species (Anonymous 2010a, b, c). In most cases, medium and high evaluated herbicide rates provided similar false-green kyllinga or purple nutsedge control, indicating that maximum use rates may not always be beneficial. Additionally, seasonal rainfall amounts may affect herbicide efficacy.

Excluding purple nutsedge in 2007, purple nutsedge and false-green kyllinga control and shoot number reduction were enhanced with two applications compared to a single application (Table 3). In 2008, two applications enhanced purple nutsedge and false-green kyllinga control by 26 and 22%, respectively. Similarly, two applications enhanced purple nutsedge and false-green kyllinga shoot number reduction by 29% in 2008 compared to a single application. Much research has been completed and concluded sequential applications are required for acceptable perennial Cyperaceae control. For example, Hubbard et al. (2007) reported 45% purple nutsedge control with a single trifloxysulfuron application while control was enhanced to 90% when a sequential was applied. Similarly, Brecke et al. (2007) reported two sulfosulfuron applications were required for acceptable purple nutsedge control.

Herbicide, Sequential Application Timing and Herbicide Rate. Little published research exists about optimum sequential application timing for sedge control with sulfonylurea herbicides. The trifloxysulfuron label suggests repeat applications four to six weeks after initial application for tough to control perennial weeds including *Kyllinga* and *Cyperus* spp. (Anonymous 2010a), whereas other sulfonylurea herbicide labels (halosulfuron) suggest repeat applications six to ten weeks after initial application (Anonymous 2010b). The sulfentrazone product label recommends applying a sequential "when evidence of actively growing purple nutsedge is visible" or "35 DAIT" (Anonymous 2010c). Hence trials were designed to compare application rates and sequential application timings of trifloxysulfuron and sulfentrazone for false-green kyllinga and purple nutsedge control.

Regardless of year, trifloxysulfuron provided greater purple nutsedge and false-green kyllinga control and shoot number reduction compared to sulfentrazone (Table 4). Trifloxysulfuron provided 70 and 69% purple nutsedge control in 2007 and 2008, respectively, while providing 100 and 83% false-green kyllinga control in 2007 and 2008, respectively. Regardless of year, sulfentrazone provided ≤ 43% purple nutsedge or false-green kyllinga control. Similar trends were observed with purple nutsedge and false-green kyllinga shoot number reduction. Trifloxysulfuron reduced purple nutsedge shoot number by 73 and 90%, respectively, in 2007 and 2008 and provided ≥ 92% false-green kyllinga shoot number reduction in both years.

The ability of plants to emerge from numerous tubers makes control of tuberous perennial sedge species difficult. Trifloxysulfuron reduced purple nutsedge tuber and false-green kyllinga rhizome viability to a greater extent than sulfentrazone (Table 4). In 2007 and 2008, trifloxysulfuron reduced purple nutsedge tuber viability by 23% and 58%, respectively. Although significantly reduced compared to the nontreated, sulfentrazone treatments only reduced purple nutsedge tuber viability ≤ 12%. As stated above, previous research reported minimal trifloxysulfuron translocation into purple nutsedge roots and tubers indicating this may be a limiting factor in effective tuber viability reduction (Troxler et al. 2003). Similarly, Nesser et al. (1997) concluded herbicidal purple nutsedge control is often suboptimal due to inconsistent herbicide translocation into tubers. Wehtje et al. (1997) reported minimal sulfentrazone translocation into purple nutsedge roots and tubers, indicating sulfentrazone may not reduce purple nutsedge tuber viability.

Herbicides must translocate shorter distances to rhizomes compared to tubers, which may have attributed to greater viability reductions in false-green kyllinga rhizomes compared to purple nutsedge tubers. Regardless of year, trifloxysulfuron reduced false-green kyllinga rhizome viability by > 90%, while sulfentrazone reduced viability by 40 and 70% in 2007 and 2008, respectively. Reducing false-green kyllinga rhizome viability by > 90% would likely result in control in subsequent years. Single year herbicide programs would likely not eradicate perennial sedge species; however, if practitioners are able to reduce rhizome viability, it may lend itself to reduced herbicide inputs in subsequent years.

Previous research suggests foliar-applied trifloxysulfuron distributes primarily in the treated leaf and primary shoot of false-green kyllinga; however, appreciable trifloxysulfuron is translocated to rhizomes and roots (McElroy et al. 2004). Once a compound inhibits acetolactate synthase (ALS), absorption and translocation within the plant determines whole plant activity (Shaner and Singh 1997). Since branched chain amino acid pathways are most active in meristematic regions (Shaner and Singh 1997), ALS herbicide translocation to rhizomes is imperative for acceptable control or viability reduction.

Excluding false-green kyllinga in 2008, sequential sulfentrazone or trifloxysulfuron applied 6 WAIT enhanced purple nutsedge and false-green kyllinga control compared to a single application or a sequential applied 4 or 8 WAIT in 2007 and 2008 (Table 5). In 2007, a sequential application applied 6 WAIT provided 63% purple nutsedge control while sequential applications applied 4 or 8 WAIT provided approximately 9-12% less control. Similarly, in 2008, a sequential application applied 6 WAIT provided 62% purple nutsedge control, but when sequential treatments were applied 8 WAIT, control was reduced to 29%. Regardless of year, single applications provided < 40% purple nutsedge control.

In 2007, sulfentrazone or trifloxysulfuron applied sequentially 6 WAIT provided the greatest false-green kyllinga control (84%) while sequential treatments applied 4 or 8 WAIT provided approximately 14% less control (Table 5). Contrarily, in 2008, timing of sequential application did not affect false-green kyllinga control although treatments containing a sequential application provided greater false-green kyllinga control compared to a single application.

Shoot number reduction followed similar trends as visual estimates of control (Table 5). Regardless of species or year, a sequential treatment applied 6 WAIT enhanced purple nutsedge and false-green kyllinga shoot number reduction compared to a single application. In 2007, a sequential applied 6 WAIT provided 75% purple nutsedge shoot number reduction, similar to results attained with sequential applications applied 8 WAIT. In 2008, sequentials applied 4 or 8 WAIT provided comparable purple nutsedge shoot number reductions although a sequential applied 8 WAIT was not as effective compared to a sequential applied 6 WAIT. Sequential application timing did not affect false-green kyllinga shoot number reduction in 2007 or 2008. Little published data exists pertaining to the effect of sequential application timing for perennial Cyperaceae control with sulfentrazone or trifloxysulfuron although much research has concluded a sequential trifloxysulfuron application is required for acceptable control (Brecke et al. 2007; McElroy et al. 2005a).

These data demonstrate a sequential application is required to obtain acceptable purple nutsedge or false-green kyllinga control. These data also indicate sequential application timing may affect purple nutsedge and false-green kyllinga control with optimum control obtained with a sequential application applied 6 WAIT.

Excluding false-green kyllinga in 2007, medium and high sulfentrazone or trifloxysulfuron rates enhanced false-green kyllinga and purple nutsedge control compared to low evaluated rates (Table 6). In 2007, purple nutsedge control was enhanced with high herbicide rate while in 2008, medium- and high-rates provided similar purple nutsedge control. In 2007, purple nutsedge control was increased approximately 10% with low, medium, and high evaluated rates providing 42, 51, and 61% control, respectively. However, in 2008, medium and high evaluated rate provided similar control. Similarly, Singh and Singh (2004) reported 42 or 63 g/ha trifloxysulfuron provided comparable yellow nutsedge control with rates greater than 21 g/ha. These data indicate that while low evaluated rates may not provide acceptable control, applying maximum application rates may not always provide greater control compared to medium rates.

Evaluated treatments provided greater false-green kyllinga control compared to purple nutsedge (Table 6). In 2007, evaluated rates provided similar false-green kyllinga control (70 – 73%). Reduced rainfall in 2007 likely reduced false-green kyllinga growth and/or vigor resulting in similar response to increasing application rate. However, in 2008, low, medium and high rate provided 46, 64, and 69% control, respectively. Hutto et al. (2007) reported greater false-green kyllinga control with 0.42 compared to 0.28 kg/ha sulfentrazone while McElroy et al. (2005a) reported similar control with 0.42 and 0.56 kg/ha.

In 2007, herbicide application rate did not significantly affect purple nutsedge or false-green kyllinga shoot number reduction. In 2008, medium and high herbicide rates provided similar shoot number reduction which was greater than the low evaluated rate. It should be noted that the low evaluated rates were lower than the recommended application rate for Cyperaceae spp. (Anonymous 2010a, b, c).

Herbicide Tank-mix Partners with Sulfentrazone for Purple Nutsedge Control. Past research indicates purple nutsedge control with sulfentrazone may be inconsistent. Therefore, trials were designed to evaluate single applications of sulfentrazone and various tank-mix partners to determine if purple nutsedge control may be enhanced.

In 2007 and 2008, single applications of sulfentrazone tank-mixed with halosulfuron or trifloxysulfuron provided unacceptable (< 50%) purple nutsedge control, while sulfentrazone tank-mixed with sulfosulfuron provided greater control (79%) in 2007 (Table 7). While greater than sulfentrazone alone, tank-mixes with halosulfuron, sulfosulfuron or trifloxysulfuron provided $\leq$ 40% control in 2008. While some numerical differences were present with shoot number reduction, no significant differences were observed among tank-mix partners. Furthermore, in 2007, all tank-mixes reduced shoot number reduction compared to sulfentrazone alone.

In 2007, sulfentrazone alone or tank-mixed with sulfosulfuron or trifloxysulfuron reduced purple nutsedge tuber viability similarly, 16-21% compared to nontreated (Table 7). In 2008, trifloxysulfuron tank-mixed with sulfentrazone reduced purple nutsedge tuber viability greatest (26%) compared to other tank-mixes and sulfentrazone applied alone. While subtle differences were observed, tank-mix partner application rate did not affect purple nutsedge control or shoot number reduction (Table 8). These data indicate sulfentrazone may not provide acceptable postemergent purple nutsedge control in bermudagrass areas and attempts to increase control with tank-mix partners were not consistent.

This research indicates sulfosulfuron or trifloxysulfuron can provide acceptable false-green kyllinga and purple nutsedge control in turf environments including bermudagrass and other tolerant species, although repeat applications will likely be required. This research also indicates weather conditions, particularly rainfall, may affect perennial sedge control with evaluated herbicides. Sedge control varied up to 40% between 2007 and 2008 which the authors feel was due in large part to rainfall differences. Further, our results indicate that repeat applications applied six WAIT provided the highest level of control while highest evaluated rates did not always enhance false-green kyllinga or purple nutsedge control compared to medium or low rates. Efforts to enhance purple nutsedge control with sulfentrazone timings, rates, and tank-mix partners were inconsistent. These data confirm sulfosulfuron or trifloxysulfuron offer acceptable perennial sedge control and may be incorporated into a comprehensive integrated pest management plan.

Sources of Materials

[1] Sulfentrazone, Dismiss®, FMC Professional Solutions, Philadelphia, PA 19103.

[2] Sulfosulfuron, Certainty®, Monsanto Company, St. Louis, MO 63167.

[3] Trifloxysulfuron, Monument®, Syngenta Crop Protection Inc., Greensboro, NC 27409.

[4] Nonionic surfactant, X-77 Spreader®, Loveland Industries Inc., Greeley, CO 80632.

[5] TeeJet® Extended Range flat-fan spray nozzles, Spraying Systems Co., Wheaton, IL 60189.

[6] Metro-mix 350®, Sun-Gro Horticultural Distribution Inc., Bellevue, WA 98008.

[7] Statistical Analysis Software®, version 9.2, SAS Institute Inc., Cary, NC 27513.

[8] Halosulfuron, Sedgehammer®, Gowan Company, Yuma, AZ 85364.

Acknowledgments

The authors express appreciation to Jared Hoyle and Leon Warren for technical assistance and the following for the cooperation: Chris Kelly (Plymouth Country Club), Michael Gregory (Hidden Valley Golf Club), Pat Connell (Plymouth Country Club), and Phil Kilmer (The Emerald Golf Club).

Literature Cited

Anonymous. 2010a. Certainty® herbicide product label. Monsanto Company Publication No. 71016G5-6. St. Louis, MO: Monsanto Company. 6 p.

Anonymous. 2010b. Dismiss® herbicide product label. Philadelphia, PA: FMC Corporation. 5 p.

Anonymous. 2010c. Monument® 75WG herbicide product label. Syngenta Publication No. SCP 1134A-L1A 0805. Greensboro, NC: Syngenta Crop Protection. 25 p.

Baumann, P. A., F. T. Moore, and M. E. Matocha. 2004. Purple nutsedge (*Cyperus rotundus* L.) control from sulfosulfuron applications to turfgrass. Proc. South. Weed Sci. Soc. 57:98.

Bendixen, L. E., and U. B. Nandihalli. 1987. Worldwide distribution of purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:61-65.

Blum, R. R., J. Isgrigg, III, and F. H. Yelverton. 2000. Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) control in bermudagrass (*Cynodon dactylon*) turf. Weed Technol. 14:357–365.

Brecke, B. J., D. O. Stephenson IV, and J. B. Unruh. 2005. Control of purple nutsedge (*Cyperus rotundus*) with herbicides and mowing. Weed Technol. 19:809-814.

Brecke, B. J., J. B. Unruh, A. J. Powell, and S. D. Davis. 2004. Warm-season turfgrass tolerance and weed control with ALS-inhibiting herbicides. Proc. South. Weed Sci. Soc. 57:92.

Brecke, B. J., K. C. Hutto, and J. B. Unruh. 2007. Sulfosulfuron: weed management and turfgrass tolerance. Proc. South. Weed Sci. Soc. 60:114.

Breeden, G. K. and J. S. McElroy. 2005. Yellow nutsedge (*Cyperus esculentus*) and false-green kyllinga (*Kyllinga gracillima*) control with flazasulfuron. Proc. South. Weed Sci. Soc. 58:108.

Brosnan, J. T. and J. Deputy. 2008. Centipedegrass. University of Hawai'i at Manoa. TM-14. 4 p.

Bryson, C. T. and M. S. DeFelice, eds. 2009. Weeds of the South. Athens, Georgia: University of Georgia Press.

Bryson C. T. and R. Carter. 2008. The significance of Cyperaceae as weeds. In: Sedges: Uses, Diversity, and Systematics of the Cyperaceae (eds. R.F.C. Naczi and B. A. Ford), pp. 15–101. Monographs in Systematic Botany from the Missouri Botanical Garden, St. Louis, Missouri.

Bryson, C. T., R. Carter, L. B. McCarty, and F. H. Yelverton. 1997. *Kyllinga*, a genus of neglected weeds in the continental United States. Weed Technol. 11:838-842.

Burke, I. C., S. C. Troxler, J. W. Wilcut, and W. D. Smith. 2008. Purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*) response to postemergence herbicides in cotton. Weed Technol. 22:616-621.

Chase, R. L. and A. P. Appleby. 1979. Effects of humidity and moisture stress on glyphosate control of *Cyperus rotundus* L. Weed Research. 19:241-246.

Dayan, F. E., H. M. Green, J. D. Weete, and H. G. Hancock. 1996. Postemergence activity of sulfentrazone: effects of surfactants and leaf surfaces. Weed Sci. 44:797-803.

Eizenberg, H., Y. Goldwasser, G. Achdary, and J. Hershenhorn. 2003. The potential of sulfosulfuron to control troublesome weeds in tomato. Weed Technol. 17:133-137.

Elmore, C. D. 1990. Weed Identification Guide. Champaign, IL: Southern Weed Science Society.

Grichar, W. J., B. A. Besler, and K. D. Brewer. 2003. Purple nutsedge control and potato (*Solanum tuberosum*) tolerance to sulfentrazone and halosulfuron. Weed Technol. 17:485-490.

Harrell, J. R., A. Estes, and B. McCarty. 2009. Post-emergence control on purple nutsedge. Proc. South. Weed Sci. Soc. 62:407.

Hattersley, P. W. 1983. The distribution of C_3 and C_4 grasses in Australia in relation to climate. Oecologia 57:113-128.

Henry, G. M. and B. S. Sladek. 2008. Control of yellow and purple nutsedge in bermudagrass turf with V-10142. Proc. South. Weed Sci. Soc. 61:125.

Holm, L.G., D. L. Plucknett, J. V. Pancho, and J. P. Herberger. 1977. The World's Worst Weeds; Distribution and Biology. Honolulu, Hawaii. University of Hawaii Press.

Hubbard, L. R., A. G. Estes, and L. B. McCarty. 2007. New options for purple nutsedge control in bermudagrass turf. Proc. South. Weed Sci. Soc. 60:111.

Hutto, K. C., B. J. Brecke, and J. B. Unruh. 2007. Sulfentrazone for weed management in fine turfgrass. Proc. South. Weed Sci. Soc. 60:110.

Johnson, W. C. III. and B. G. Mullinix Jr. 1997. Population dynamics of yellow nutsedge (*Cyperus esculentus*) in cropping systems in the southeastern coastal plain. Weed Sci. 45:166-171.

Kopec, D. M. and J. J. Gilbert. 2001. Sulfentrazone effects on purple nutsedge. Tucson, AZ: The 2001 Turfgrass, Landscape, and Urban IPM Research Summary. 6 p.

Lin, C. H., Y. S. Tai, D. J. Liu, and M. S. B. Ku. 1993. Photosynthetic mechanisms of weeds in Taiwan. Aust. J. Plant Phys. 20:757-769.

Lycan, D.W. and S.E. Hart. 2004. Relative tolerance of four cool-season turfgrass species to sulfosulfuron. Weed Technol. 18:977-981.

Marvin, J. W., L. B. McCarty, and A. G. Estes. 2009. Purple nutsedge control with Dismiss (sulfentrazone) year 2. Proc. South. Weed Sci. Soc. 62:383.

McCarty, L. B., J. W. Everest, D. W. Hall, T. R. Murphy, F. Yelverton. 2008. Color Atlas of Turfgrass Weeds. Second ed. Hoboken, New Jersey: John Wiley & Sons, Inc.

McElroy, J. S., F. H. Yelverton, I. C. Burke, and J. W. Wilcut. 2004. Absorption, translocation, and metabolism of halosulfuron and trifloxysulfuron in green kyllinga (*Kyllinga brevifolia*) and false-green kyllinga (*K. gracillima*). Weed Sci. 52:704-710.

McElroy, J. S., F. H. Yelverton, and L. S. Warren Jr. 2005a. Control of green and false-green kyllinga (*Kyllinga brevifolia* and *K. gracillima*) in golf course fairways and roughs. Weed Technol. 19:824-829.

McElroy, J. S., F. H. Yelverton, M. G. Burton, and C. Brownie. 2005b. Habitat delineation of green and false-green kyllinga in turfgrass systems and interrelationship of elevation and edaphic factors. Weed Sci. 53:620-630.

Mehlich, A. 1984. Photometric determination of humic matter in soils, a proposed method. Common. Soil Sci. Plant Anal. 15:1417-1422.

Molin, W. T., A. A. Maricic, R. A. Khan, and C. F. Mancino. 1999. Effect of MON 12037 on the growth and tuber viability of purple nutsedge (*Cyperus rotundus*). Weed Technol. 13:1-5.

Murphy, T. R., L. B. McCarty, D. Hall, D. L. Colvin, R. Dickens, and J. W. Everest. 1992. Weeds of Southern Turfgrasses. Gainesville, FL: Florida Coop. Ext. Serv. 208 p.

Nesser, C., R. Aguero, and C. J. Swanton. 1997. Survival and dormancy of purple nutsedge (*Cyperus rotundus*) tubers. Weed Sci. 45:784-790.

Nelson, K. A., and K. A. Renner. 2002. Yellow nutsedge (*Cyperus esculentus*) control and tuber production with glyphosate and ALS-inhibiting herbicides. Weed Technol. 16:512-519.

Shaner, D. L. and B. K. Singh. 1997. Acetohydroxyacid synthase inhibitors. Pages 69-110. In Roe, R. M., J. D. Burton, and R. J. Kuhr, eds. Herbicide Activity: Toxicology, Biochemistry, and Molecular Biology. Burke, VA: IOS Press.

Singh, S. and M. Singh. 2004. Effect of growth stage on trifloxysulfuron and glyphosate efficacy in twelve weed species of citrus groves. Weed Technol. 18:1031-1036.

Stoller, E. W. and R. D. Sweet. 1987. Biology and life cycle of purple and yellow nutsedges (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:66-73.

Summerlin, Jr., J. R., H. D. Coble, F. H. Yelverton. 2000. Effect of mowing on perennial sedges. Weed Sci. 48:501-507.

Teeri, J. A. and L. G. Stowe. 1976. Climatic patterns and the distribution of C4 grasses in North America. Oecologia 23:1-12.

Troxler, S. C., I. C. Burke, J. W. Wilcut, W. D. Smith, and J. D. Burton. 2003. Absorption, translocation, and metabolism of foliar-applied CGA-362622 in purple and yellow nutsedge (*Cyperus rotundus* L. and *C. esculentus* L.). Weed Sci. 51:13–18.

United States Department of Agriculture. 2010a. Natural Resources Conservation Services, National Cooperative Soil Survey. http://soils.usda.gov/ Accessed February 01 2011.

United States Department of Agriculture. 2010b. Plants Profile, Natural Resources Conservation Service. http://plants.usda.gov/java/profile?symbol=KYGR. Accessed May 23 2010.

Unruh, J. B. and B. J. Brecke. 2006. New options for managing weeds in the landscape. Jay, FL: Florida Coop. Ext. Serv. ENH1039. 3 p.

Wehtje, G. R., R. H. Walker, T. L. Grey, and H. G. Hancock. 1997. Response of purple (*Cyperus rotundus*) and yellow nutsedges (*C. esculentus*) to selective placement of sulfentrazone. Weed Sci. 45:382-387.

Willis, J.B., D.B. Ricker, S.D. Askew. 2007. Sulfonylurea herbicides applied during early establishment of seeded bermudagrass. Weed Technol. 21:1035-1038.

Wills G.D. 1987. Description of Purple and Yellow Nutsedge (Cyperus rotundus and C. esculentus). Weed Technol. 1:2-9.

Yelverton F. 1996. Know Your Sedges, Golf Course Manage. pp. 56-60.

Zar J. H. 1999. Biostatistical analysis. 4th ed. Upper Saddle River: New Jersey Prentice Hall.

Table 1. Influence of herbicide on purple nutsedge or false-green kyllinga control, shoot number reduction and tuber or rhizome viability 12 WAIT.[a]

	CYPRO						KYLGR					
	Control[b]		Shoot number reduction[c]		Tuber viability[d]		Control[b]		Shoot number reduction[c]		Rhizome viability[d]	
Herbicide	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
	%											
Sulfentrazone	21	29	19	32	88	89	44	51	58	53	40	21
Sulfosulfuron	92	50	98	65	33	51	91	61	87	79	13	0
Trifloxysulfuron	77	58	88	69	69	71	100	80	98	83	13	0
Nontreated	0	0	-	-	100	100	0	0	-	-	100	100
$LSD_{0.05}$	5	5	23	16	14	8	6	6	9	15	14	7

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

[d] Percent viability calculated from shoot emergence from harvested CYPRO tubers or KYLGR rhizomes.

Table 2. Influence of herbicide application rate on purple nutsedge or false-green kyllinga control and shoot number reduction 12 WAIT.[a]

	CYPRO				KYLGR			
	Control[b]		Shoot number reduction[c]		Control[b]		Shoot number reduction[c]	
Herbicide rate	2007	2008	2007	2008	2007	2008	2007	2008
	%							
Low	55	37	64	43	66	48	69	57
Medium	63	49	62	60	82	67	87	76
High	71	52	79	63	87	76	88	81
$LSD_{0.05}$	5	5	NS	16	6	6	9	15

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference; NS, nonsignificant.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

Table 3. Influence of sequential herbicide application on purple nutsedge or false-green kyllinga control and shoot number reduction 12 WAIT.[a]

	CYPRO				KYLGR			
	Control[b]		Shoot count reduction[c]		Control[b]		Shoot count reduction[c]	
No. applications	2007	2008	2007	2008	2007	2008	2007	2008
	%							
1	61	33	64	41	68	53	69	57
2	65	59	72	70	89	75	94	86
$LSD_{0.05}$	NS	4	NS	13	5	6	7	13

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference; NS, nonsignificant.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

Table 4. Influence of herbicide on purple nutsedge or false-green kyllinga control, shoot number reduction and tuber or rhizome viability 12 WAIT.[a]

	CYPRO						KYLGR					
	Control[b]		Shoot number reduction[c]		Tuber viability[d]		Control[b]		Shoot number reduction[c]		Rhizome viability[d]	
Herbicide	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
	%											
Sulfentrazone	32	20	51	61	90	88	43	37	37	58	60	30
Trifloxysulfuron	70	69	73	90	77	42	100	83	100	92	8	5
Nontreated	0	0	-	-	100	100	0	0	-	-	100	100
$LSD_{0.05}$	4	3	16	7	8	6	3	3	10	5	10	11

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

[d] Percent viability based on shoot emergence from harvested tubers or rhizomes which were planted in greenhouse.

Table 5. Influence of sequential application timing on purple nutsedge or false-green kyllinga control and shoot number reduction 12 WAIT.[a]

	CYPRO				KYLGR			
	Control[b]		Shoot number reduction[c]		Control[b]		Shoot number reduction[c]	
Sequential timing	2007	2008	2007	2008	2007	2008	2007	2008
	%							
No sequential	38	35	52	65	62	54	60	60
4 WAIT	51	54	51	78	69	64	71	77
6 WAIT	63	62	75	86	84	62	78	83
8 WAIT	54	29	71	74	70	60	66	80
$LSD_{0.05}$	6	4	22	10	4	5	15	7

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

Table 6. Influence of herbicide application rate on purple nutsedge or false-green kyllinga control and shoot number reduction 12 WAIT.[a]

	CYPRO				KYLGR			
	Control[b]		Shoot number reduction[c]		Control[b]		Shoot number reduction[c]	
Herbicide rate	2007	2008	2007	2008	2007	2008	2007	2008
	%							
Low	42	36	59	68	70	46	68	71
Medium	51	48	61	80	73	64	64	77
High	61	50	67	79	71	69	74	77
$LSD_{0.05}$	5	4	19	9	4	4	13	6

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; KYLGR, false-green kyllinga; LSD, least significant difference.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

Table 7. Influence of sulfentrazone tank-mix partner on purple nutsedge control, shoot number reduction and tuber viability 12 WAIT.[a]

	Control[b]		Shoot number reduction[c]		Tuber viability[d]	
Tank-mix partner	2007	2008	2007	2008	2007	2008
	%					
Halosulfuron	49	31	22	24	93	90
Sulfosulfuron	79	40	52	49	79	85
Trifloxysulfuron	42	38	43	44	84	74
Sulfentrazone alone	34	18	-20	19	83	88
Nontreated	0	0	-	-	100	100
$LSD_{0.05}$	10	6	57	30	13	9

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; LSD, least significant difference.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

[d] Percent viability based on shoot emergence from harvested tubers which were planted in greenhouse.

Table 8. Influence of sulfentrazone tank-mix rate on purple nutsedge control and shoot number reduction 12 WAIT.[a]

	Control[b]		Shoot number reduction[c]	
Tank-mix rate	2007	2008	2007	2008
	——— % ———			
0.5X	58	31	7	34
1X	55	42	29	44
$LSD_{0.05}$	NS	5	NS	NS

[a] WAIT, weeks after initial treatment; CYPRO, purple nutsedge; LSD, least significant difference; NS, not significant.

[b] Percent control based on visual estimates (0 = no visual symptoms; 100 = complete plant death).

[c] Percent shoot number reduction relative to nontreated.

Appendix

Table A1. Daily rainfall (cm), Plymouth, NC, 2007.[a]

Day	June	July	August	September
1	-	0.79	-	-
2	-	-	-	-
3	2.41	-	-	-
4	1.78	-	-	-
5	-	-	-	-
6	-	-	0.08	-
7	-	1.52	-	-
8	-	-	-	-
9	-	-	0.76	0.13
10	-	0.46	2.41	-
11	-	0.48	0.46	-
12	0.23	1.12	-	-
13	-	0.03	-	-
14	0.36	-	-	-
15	-	-	-	1.93
16	0.25	-	-	-
17	0.86	0.03	0.08	-
18	-	1.52	-	-
19	0.08	-	-	0.08
20	0.05	0.05	-	0.69
21	-	-	-	0.91
22	-	-	3.89	0.25
23	-	-	-	-
24	-	-	-	-
25	-	-	-	-
26	2.18	-	-	-
27	-	0.51	0.08	0.15
28	-	-	0.03	0.05
29	0.13	-	-	-
30	0.03	1.12	-	-
31	N/A	-	-	N/A
Sum	8.36	7.62	7.77	4.19

[a] Rainfall recorded by State Climate Office of North Carolina, 7.8 km from Plymouth Country Club.

Table A2. Daily rainfall (cm), Fuquay Varina, NC, 2007.[a]

Day	June	July	August	September
1	-	-	-	-
2	-	-	-	-
3	7.95	-	-	-
4	0.08	-	-	-
5	-	-	-	-
6	0.13	-	-	-
7	-	-	-	-
8	-	-	-	-
9	-	-	-	-
10	0.48	0.25	-	-
11	-	0.30	-	-
12	0.03	0.43	-	-
13	4.45	-	-	-
14	-	-	-	-
15	0.05	-	-	4.39
16	-	-	-	-
17	-	-	-	-
18	-	9.55	-	-
19	-	-	-	0.03
20	0.33	-	-	0.10
21	-	-	-	0.15
22	-	-	0.86	-
23	-	-	1.19	-
24	-	-	-	-
25	0.46	-	-	-
26	-	-	-	-
27	-	-	0.97	-
28	-	0.89	-	-
29	-	-	-	-
30	0.18	-	-	-
31	N/A	0.33	-	N/A
Sum	14.12	11.76	3.02	4.67

[a] Rainfall recorded by State Climate Office of North Carolina, 14.1 km from Hidden Valley Golf Club.

Table A3. Daily rainfall (cm), New Bern, NC, 2008.[a]

Day	June	July	August	September
1	-	-	-	-
2	-	-	0.05	-
3	-	-	-	-
4	-	-	-	-
5	-	0.71	-	-
6	-	4.62	-	0.81
7	-	0.03	0.33	-
8	-	0.69	-	0.81
9	-	0.36	-	2.01
10	-	-	0.13	0.18
11	-	0.03	0.46	-
12	-	-	-	-
13	-	-	2.49	-
14	0.03	-	-	-
15	-	-	-	2.31
16	-	-	-	-
17	-	-	-	0.03
18	-	0.08	-	-
19	-	0.61	2.36	-
20	-	1.47	-	-
21	0.23	-	-	-
22	0.91	-	-	-
23	-	-	-	-
24	-	1.52	-	-
25	-	-	-	6.38
26	-	-	0.03	1.35
27	-	0.20	1.88	-
28	0.89	0.25	2.77	-
29	-	-	-	-
30	0.03	-	-	2.51
31	N/A	2.11	0.05	N/A
Sum	2.08	12.67	10.54	18.69

[a] Rainfall recorded by State Climate Office of North Carolina, 5.0 km from New Bern Country Club; 5.6 km from The Emerald Golf Club.

SELECTIVE EXPOSURE OF YELLOW NUTSEDGE (*CYPERUS ESCULENTUS*), PURPLE NUTSEDGE (*CYPERUS ROTUNDUS*) AND FALSE-GREEN KYLLINGA (*KYLLINGA GRACILLIMA*) TO POSTEMERGENCE HERBICIDES.

Formatted for Weed Technology

Travis W. Gannon, Fred H. Yelverton and Lane P. Tredway*

Greenhouse experiments were conducted to evaluate the effect of selective herbicide placement on sedge shoot number, shoot weight and root weight. Sulfentrazone, sulfosulfuron and trifloxysulfuron were applied to the soil only, foliage only, or soil + foliage. Yellow nutsedge and false-green kyllinga were more sensitive than purple nutsedge to sulfentrazone. Purple nutsedge and false-green kyllinga are more susceptible than yellow nutsedge to sulfosulfuron, while evaluated species responded similarly to trifloxysulfuron. Soil- and soil + foliar-applied herbicides provided the highest level of growth suppression, indicating herbicide-soil contact is required for optimum sedge control. Future research should evaluate techniques that optimize herbicide-soil contact to improve herbicide efficacy.

Received for publication __________ and in approved form __________.

* First and second authors: Research Associate and Professor, Department of Crop Science, North Carolina State University, Raleigh, NC 27695; Third author: Associate Professor, Department of Plant Pathology, North Carolina State University, Campus Box 7616, Raleigh, NC 27695. Corresponding author's E-mail: travis_gannon@ncsu.edu.

Nomenclature: sulfentrazone; sulfosulfuron; trifloxysulfuron; false-green kyllinga, *Kyllinga gracillima* L.; purple nutsedge, *Cyperus rotundus* L.; yellow nutsedge, *Cyperus esculentus* L.

Key words: Foliar absorption, herbicide efficacy, root absorption, sedge control.

Purple nutsedge (*Cyperus rotundus* L.), yellow nutsedge (*Cyperus esculentus* L.) and false-green kyllinga (*Kyllinga gracillima* Miq.) are common perennial sedges in turfgrass systems that prefer above normal soil moisture (Bendixen and Nandihalli 1987; Bryson et al. 1997; McCarty et al. 2008; McElroy et al. 2005b). Although each may survive routine mowing, purple nutsedge growth may be suppressed with typical golf course fairway mowing height while false-green kyllinga is able to withstand frequent mowing at 1.3 cm (Bryson et al. 1997; Summerlin et al. 2000). Yellow nutsedge is not generally observed in mowing heights typical of a golf course fairway and is more commonly observed in higher mowing heights and nonmown areas (Summerlin 1997). Each species exhibits prolific vegetative growth and produces rhizomes; purple and yellow nutsedge also produce basal bulbs and tubers (McCarty et al. 2008; Stoller and Sweet 1987).

Native to India and named for its infloresence color, purple nutsedge is a rapidly spreading perennial with three-ranked basal leaves typically shorter than the flowering stem (Chase and Appleby 1979; McCarty et al. 2008). Although purple nutsedge is not as widely distributed as other *Cyperus* species, it has been described as the "world's worst weed" because it is a serious competitor with more crops than any other weed (Holm et al. 1977). Although purple nutsedge produces seed, basal bulbs and chains of tubers are the primary means of dispersal (Murphy et al. 1992; Stoller and Sweet 1987; Wills 1987).

Native to North America, yellow nutsedge has been described as one of the world's worst weeds (Stoller and Sweet 1987). Yellow nutsedge is able to survive cooler climates and is more widely distributed than purple nutsedge (Martínez-Ochoa et al. 2004; McCarty et al. 2008; Stoller and Sweet 1987). This may be due to its ability to increase tuber starch, sugar and lipid content in response to temperature (Bendixen and Nandihalli 1987). Yellow nutsedge produces seed, basal bulbs and tubers (Stoller et al. 1972). Unlike purple nutsedge, yellow nutsedge does not produce tuber chains. Further, yellow nutsedge is cultivated for edible tubers in southern Europe and Africa (Bryson et al. 2009; Wills 1987).

Native to Asia, false-green kyllinga is an aromatic, rhizomatous perennial which is able to produce fruit below mowing heights < 1.25 cm, providing a reproductive advantage in managed turfgrasses (Bryson et al. 1997; McElroy et al. 2002; Summerlin et al. 2000). False-green kyllinga is similar vegetatively to green kyllinga (*Kyllinga brevifolia* Rottb.) but can be differentiated by seed morphology or flower timing (Bryson et al. 1997). Scale keels of green and false-green kyllinga seed are denticulate and smooth, respectively (Bryson et al. 1997). False-green kyllinga flowering is photoperiod-dependent, occurring late-summer until frost while green kyllinga flowers during most summer months (Bryson et al. 1997; McCarty et al. 2008).

The incidence of sedge species has increased in recent years in turfgrass systems, likely due in part to changes in herbicide programs (Yelverton 1996). Traditionally, monosodium methylarsonate (MSMA) used for postemergent (POST) crabgrass (*Digitaria* spp.) and goosegrass (*Eleusine indica* (L.) Gaertn.) control also controlled *Cyperus* and *Kyllinga* species. With the widespread adoption of preemergent (PRE) herbicides and less dependence on POST herbicides, these species are becoming more prevalent in turfgrass systems.

Sulfentrazone is an aryl triazolinone herbicide developed for PRE and POST weed control in soybean, tobacco, sunflower, sugarcane and turfgrass (Senseman 2007). Sulfentrazone is a protoporphyrinogen oxidase inhibitor which disrupts cell membranes (Senseman 2007). Sulfentrazone product labels allow application up to 420 g ai ha^{-1} in select cool- and warm-season turfgrasses (Anonymous 2010a). Sulfentrazone controls numerous annual and perennial grass, broadleaf and sedge species including false-green kyllinga, green kyllinga and yellow nutsedge (Anonymous 2010a; McElroy et al. 2005a). Sulfosulfuron is a sulfonylurea (SU) herbicide developed for POST weed control in wheat and turfgrass (Senseman 2007). Select warm- and cool-season turfgrasses have exhibited tolerance to sulfosulfuron up to 105 g/ha (Anonymous 2010b; Lycan and Hart 2004; Willis et al. 2007). Sulfosulfuron controls select annual and perennial grass and sedge species including yellow and purple nutsedge and green- and false-green kyllinga (Anonymous 2010b; Eizenberg et al. 2003). Trifloxysulfuron is another SU herbicide currently registered for POST weed control in cotton (*Gossypium hirsutum* L.), sugarcane (*Saccharum* spp.) and turfgrasses (Anonymous 2010c; Brecke and Unruh 2000; Hudetz et al. 2000; Porterfield et al. 2002; Wells et al. 2000). Bermudagrass (*Cynodon dactylon* (L.) Pers.) and St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze) have exhibited trifloxysulfuron tolerance up to 40 g ha^{-1} (Teuton et al. 2001; Yelverton et al. 2002). Trifloxysulfuron controls select cool-season grasses, annual and perennial sedges including yellow nutsedge, purple nutsedge, green kyllinga, false-green kyllinga and numerous broadleaf species (Anonymous 2010c; McElroy et al. 2005; Yelverton et al. 2002). Sulfonylurea herbicides inhibit the activity of the acetolactate synthase (ALS) enzyme. Disruption of this metabolic process inhibits the production of essential amino acids including leucine, isoleucine and valine required for production of new cells (Senseman 2007).

Herbicide efficacy may be governed by the effect of herbicide placement and site of uptake and action. Effects of selective herbicide placement on sedge control have been previously reported (McElroy et al. 2003; McElroy et al. 2004; Nandihalli and Bendixen

1998; Reddy and Bendixen 1998; Vencill et al. 1995; Wehtje et al. 1997). However, information regarding the response of sedge species to currently available herbicides is limited. The objective of this research was to determine the effect of POST herbicide placement on purple nutsedge, yellow nutsedge and false-green kyllinga growth.

Materials and Methods

Greenhouse experiments were conducted to investigate the effect of soil, foliar and soil + foliar applications of sulfentrazone, sulfosulfuron and trifloxysulfuron on false-green kyllinga, purple nutsedge and yellow nutsedge growth. Trials were conducted at North Carolina State University Method Road Greenhouse Laboratory during 2007 and 2008. Greenhouse temperatures were maintained at 32/24 C day/night and plants were irrigated from overhead three times daily. Supplemental lighting (350 µmol m^{-2} s^{-1}) was provided with metal halide lamps (1000 watts) to simulate a 16 h daylength. The growing medium was a 1:1 v v^{-1} ratio of river-bottom sand and Norfolk loamy fine sand (thermic Typic Kandiudults) with pH 6.2 and 0.4% humic matter.

Purple and yellow nutsedge tubers[1] were purchased while false-green kyllinga rhizomes were collected locally. A single yellow or purple nutsedge tuber or node from a false-green kyllinga rhizome was planted at 1 cm depth in each pot filled with growing medium (103 cm^2, 1050 mL v). Additional pots were planted to allow selection of uniform

[1] Azlin Seed Service, 2007. PO Box 914, Leland MS 38756.

plants at experiment initiation. Plants were fertilized biweekly with 20-20-20 water-soluble fertilizer[2] to provide 2.4 g nitrogen m^{-2}.

Experiments were initiated 28 d after planting (DAP) at which time purple nutsedge averaged 3 – 5 leaves and 5.1 cm in height while yellow nutsedge averaged 4 – 6 leaves and 10.2 cm in height. False-green kyllinga averaged 6 – 12 leaves and 5.1 cm in height. After treatment, plants were not irrigated for 24 h. Through 30 DAT, irrigation was applied to the soil surface by hand daily with careful attention paid not to contact foliage or over-irrigate to prevent washing herbicide from plant foliage and leaching through the soil. After 30 DAT, overhead irrigation was resumed.

Experiments were conducted as a randomized complete block design with a three by three by three factorial arrangement of treatments with four replications. Factorial levels included three sedge species (purple nutsedge, yellow nutsedge and false-green kyllinga), three herbicide placements (soil only, foliage only or soil + foliage) and three herbicide treatments (sulfentrazone, sulfosulfuron or trifloxysulfuron). A nontreated was included for each species and pots were rerandomized weekly to minimize the effect of variation in the greenhouse. The experiment was repeated over time with two runs in each of two years.

Foliar and foliar + soil treatments were applied with a hand-held CO_2-propelled sprayer calibrated to deliver 304 L ha^{-1} with one 8002E flat fan nozzle[3] at 193 kPa. For foliar treatments, herbicide was prevented from contacting the soil by placing a 2 cm thick layer of

---

[2] Peters Professional 20-20-20 Water-Soluble Fertilizer; Scotts-Sierra Horticultural Products Co., 14111 Scottslawn Rd. Marysville, OH 43041.

[3] TeeJet® flat-fan spray nozzles, Spraying Systems Co., PO Box 7900 Wheaton, IL 60189.

activated charcoal[4] on the soil surface prior to herbicide treatment. Foliage was allowed to dry prior to removing activated charcoal. Soil treatments were applied by diluting the amount of spray solution that would contact the soil surface in 10 mL tap water and uniformly applying to the soil surface. Herbicide treatments included: sulfentrazone[5] (336 g ai ha^{-1}), sulfosulfuron[6] (53 g ai ha^{-1}) and trifloxysulfuron[7] (22 g ai ha^{-1}). Sulfosulfuron and trifloxysulfuron treatments included a nonionic surfactant[8] (NIS) (0.25% v v^{-1}).

The number of emerged shoots was recorded 30 and 60 DAT. At 30 and 60 DAT, shoots were clipped at the soil surface, dried for 96 h at 60 C and 0% relative humidity and weights were recorded. At 60 DAT, roots were washed free of soil, dried as previously described and weights were recorded. Percent shoot number, shoot weight and root weight reductions, relative to the nontreated, were calculated by:

$$(((\text{Nontreated} - \text{treated})/\text{nontreated}) \times 100) \quad [1]$$

---

[4] Aquatrols Clean Carbon, 5 North Olney Avenue, Cherry Hill, NJ 08003.

[5] Sulfentrazone, Dismiss®, FMC Professional Solutions, 1735 Market Street, Philadelphia, PA 19103.

[6] Sulfosulfuron, Certainty®, Monsanto Company, 800 North Lindbergh Street, St. Louis, MO 63167.

[7] Trifloxysulfuron, Monument®, Syngenta Crop Protection Inc., 410 South Swing Road, Greensboro, NC 27409.

[8] X-77® Spreader (alkylarylpolyoxyethylene glycols, free fatty acids, isopropanol), Loveland Industries, Inc., PO Box 1289 Greeley CO 80632.

Data were subject to ANOVA ($P = 0.05$). Significant ($P < 0.05$) main effects and interactions are presented accordingly with precedent given to higher order interactions (Steele et al. 1997). Experimental run main effect and their interactions were not significant; therefore, data were pooled over runs. Means were separated according to Fisher's protected LSD using SAS general linear model.

Results and Discussion

Significant interactions among herbicide and sedge species prevented pooling of data. Pooled across herbicide placement, sulfentrazone reduced yellow nutsedge shoot number and shoot weight greater than purple nutsedge (Table 1). Sulfentrazone reduced yellow nutsedge and false-green kyllinga shoot number and shoot weight 64 – 77%, relative to the nontreated, while purple nutsedge was reduced ≤ 52%. Further, sulfentrazone reduced yellow nutsedge (75%) root weight to a greater extent than purple nutsedge (51%) and false-green kyllinga (56%). Previous research has reported acceptable yellow nutsedge and false-green kyllinga control with sulfentrazone while purple nutsedge control was < 50% (Blum et al. 2000; McElroy et al. 2005a).

Sulfosulfuron reduced purple nutsedge and false-green kyllinga shoot number, shoot weight and root weight greater than yellow nutsedge. Purple nutsedge and false-green kyllinga shoot number, shoot weight and root weight were reduced ≥ 73% while yellow nutsedge was reduced ≤ 55%. Contrary to these data, Hart and McCullough (2009) reported sulfosulfuron provided > 85% yellow nutsedge control. Previous research has reported acceptable purple nutsedge and false-green kyllinga control with sulfosulfuron (Baumann et al. 2004; Brecke et al. 2007; Eizenberg et al. 2003; Harrell et al. 2009; Yelverton et al. 2008).

Trifloxysulfuron reduced shoot number and shoot weight > 75%, regardless of species. Further, trifloxysulfuron reduced purple nutsedge and false-green kyllinga root weight ≥ 79%. Previous research has indicated trifloxysulfuron effectively controls yellow and purple nutsedge as well as green and false-green kyllinga (Brecke and Unruh 2000; McElroy et al. 2005; Teuton et al. 2001; Yelverton et al. 2008). Burke et al. (2008) reported trifloxysulfuron effectively reduced yellow and purple nutsedge shoot and root dry weight, although reduction was influenced by plant height at application.

Soil- and soil + foliar-applied sulfentrazone, sulfosulfuron and trifloxysulfuron provided greater shoot number, shoot weight and root weight reduction than foliar applications 60 DAT (Table 2). Further, soil-applied sulfentrazone provided greater shoot number reduction than soil + foliar applications. Soil-applied sulfentrazone reduced shoot number 95% while soil + foliar and foliar applications provided 66 and 5% shoot number reduction, respectively, relative to the nontreated. Foliar-applied sulfentrazone provided minimal (< 15%) shoot and root weight reduction. Soil-applied sulfentrazone likely provided greater reduction because it increased root-available sulfentrazone compared to foliar or soil + foliar applications where sulfentrazone was retained on the foliage. Wehtje et al. (1997) reported foliar-applied sulfentrazone had minimal effect on yellow and purple nutsedge and acceptable control required soil contact. Further, Wehtje et al. (1997) concluded the amount of sulfentrazone in purple nutsedge foliage was less compared to yellow nutsedge, possibly indicating purple nutsedge absorbs less sulfentrazone. Although absorbed by roots and shoots, sulfentrazone phloem mobility is limited, and foliar-only applications may provide localized symptoms but may be ineffective for complete or long-term control. In contrast, root-absorbed sulfentrazone is readily translocated to yellow and purple nutsedge foliage

(Senseman 2007; Wehtje et al. 1997). Thomas et al. (2005) reported ≥ 39% of root-absorbed sulfentrazone was translocated to leaves of treated plants. These data indicate sulfentrazone activity on false-green kyllinga, purple nutsedge and yellow nutsedge is highly dependent on soil exposure, indicating practices that increase sulfentrazone-soil contact may increase efficacy.

Soil- and soil + foliar-applied sulfosulfuron provided ≥ 85% shoot number and shoot weight reduction and ≥ 77% root weight reduction 60 DAT (Table 2). Foliar applications provided < 45% shoot number, shoot weight and root weight reduction. Sulfosulfuron is an ALS-inhibiting herbicide that is root- and foliar-absorbed (Senseman 2007). Although published research is not available comparing the activity of root- and foliar-applied sulfosulfuron, foliar + soil or soil-only applications of other ALS-inhibiting herbicides have been reported to be more effective than foliar-only applications (Williams et al. 2001). Further, Richburg et al. (1993, 1994) reported soil- and soil + foliar applications of the ALS-inhibiting herbicides imazethapyr and imazapic reduced yellow and purple nutsedge shoot regrowth greater than foliar applications.

Soil- and soil + foliar-applied trifloxysulfuron provided ≥ 98% shoot number and shoot weight reduction while foliar applications provided less reduction (< 50%) (Table 2). Soil- and soil + foliar-applied trifloxysulfuron also provided greater root weight reduction than foliar applications. Although soil- and soil + foliar-applied trifloxysulfuron reduced root weight 86%, harvested roots were partially decayed and were not healthy indicating root weight may have been overestimated. Within this research, foliar applications did not provide similar reduction as soil or soil + foliar applications. McElroy et al. (2003, 2004) reported soil- and soil + foliar-applied trifloxysulfuron reduced purple nutsedge, yellow nutsedge and green kyllinga growth greater than foliar-applied trifloxysulfuron. Further, McElroy et al. (2003) reported soil-applied trifloxysulfuron reduced yellow and purple nutsedge shoot number greater than foliar and soil + foliar applications 60 DAT. Previous research has reported soil + foliar applications of another SU herbicide, halosulfuron, reduced yellow nutsedge shoot growth greater than foliar-only applications (Vencill et al. 1995). Further, Wilcut et al. (1998) reported soil + foliar-applied pyrithiobac, another ALS-inhibiting herbicide, reduced purple and yellow nutsedge shoot number greater than soil- or foliar-only applications. ALS-inhibiting herbicides are readily absorbed by roots and foliage and are xylem- and phloem-mobile to the site of action in meristematic regions (Senseman 2007). This indicates acceptable control with ALS-inhibiting herbicides may not be as dependent on specific exposure compared to an herbicide that is not phloem-mobile such as sulfentrazone. Further, in field applications, the amount of potentially available herbicide for root absorption may be dictated by the plant canopy with soil-applied herbicides having greater herbicide available for root absorption because of the lack of foliar interception. These data indicate soil-applied ALS-inhibiting herbicides are equally effective as soil + foliar applications.

Pooled across herbicides, soil and foliar applications provided similar yellow nutsedge, purple nutsedge and false-green kyllinga shoot number and shoot weight reduction 60 DAT (Table 3). Soil applications provided $\geq$ 87% and $\geq$ 93% shoot number and shoot weight reduction, respectively, relative to the nontreated, while foliar applications reduced shoot number and shoot weight $\leq$ 37%. Soil applications reduced root weight 76 – 91% while foliar applications reduced root weight $\leq$ 43%, regardless of species. Soil + foliar-applied herbicides reduced yellow nutsedge and false-green kyllinga shoot number and shoot weight $\geq$ 95% 60 DAT while purple nutsedge shoot number and shoot weight were reduced less (65 and 85%, respectively). Soil + foliar applications provided greater false-green kyllinga root weight reduction than yellow and purple nutsedge. McElroy et al. (2003) reported foliar- and soil + foliar-applied trifloxysulfuron, imazaquin, MSMA and imazaquin + MSMA provided greater yellow nutsedge shoot number reduction compared to soil-applications while soil and soil + foliar applications provided greater purple nutsedge shoot number reduction compared to foliar applications. These data and previous research indicate the effect of herbicide placement is likely dependent on species and herbicide.

Based on evaluated parameters, yellow nutsedge and false-green kyllinga are more susceptible to sulfentrazone than purple nutsedge. Further, purple nutsedge and false-green kyllinga are more susceptible to sulfosulfuron than yellow nutsedge, while evaluated species responded similarly to trifloxysulfuron. Soil-applied sulfentrazone, sulfosulfuron and trifloxysulfuron provided the highest level of control indicating herbicide-soil contact is imperative for optimum sedge control. In most cases, soil + foliar-applications provided growth reduction comparable to soil applications whereas foliar applications provided less growth reduction. While sulfentrazone, sulfosulfuron and trifloxysulfuron are shoot- and root-absorbed, unlike sulfosulfuron and trifloxysulfuron, sulfentrazone is not phloem-mobile possibly compromising perennial sedge control if soil contact is not ensured (Senseman 2007). Future research should evaluate techniques that encourage herbicide-soil contact possibly including light irrigation after application or application when minimal foliage is present such as immediately after mowing.

Literature Cited

Anonymous. 2010a. Certainty® herbicide product label. Monsanto Company Publication No. 71016G5-6. St. Louis, MO: Monsanto Company. 6 p.

Anonymous. 2010b. Dismiss® herbicide product label. Philadelphia, PA: FMC Corporation. 5 p.

Anonymous. 2010c. Monument® 75WG herbicide product label. Syngenta Publication No. SCP 1134A-L1A 0805. Greensboro, NC: Syngenta Crop Protection. 25 p.

Baumann, P. A., F. T. Moore, and M. E. Matocha. 2004. Purple nutsedge (*Cyperus rotundus* L.) control from sulfosulfuron applications to turfgrass. Proc. South. Weed Sci. Soc. 57:98.

Bendixen, L. E., and U. B. Nandihalli. 1987. Worldwide distribution of purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:61-65.

Blum, R. R., J. Isgrigg, III, and F. H. Yelverton. 2000. Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) control in bermudagrass (*Cynodon dactylon*) turf. Weed Technol. 14:357–365.

Brecke, B. J. and J. B. Unruh. 2000. CGA-362622 for torpedograss (*Panicum repens*) and purple nutsedge (*Cyperus rotundus*) control in bermudagrass. Proc. South. Weed Sci. 53:228.

Brecke, B. J., K. C. Hutto, and J. B. Unruh. 2007. Sulfosulfuron: weed management and turfgrass tolerance. Proc. South. Weed Sci. Soc. 60:114.

Bryson, C. T. and M. S. DeFelice, eds. 2009. Weeds of the South. Athens, Georgia: University of Georgia Press.

Bryson, C. T., R. Carter, L. B. McCarty, and F. H. Yelverton. 1997. *Kyllinga*, a genus of neglected weeds in the continental United States. Weed Technol. 11:838-842.

Burke, I. C., S. C. Troxler, J. W. Wilcut, and W. D. Smith. 2008. Purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*) response to postemergence herbicides in cotton. Weed Technol. 22:615-621.

Chase, R. L. and A. P. Appleby. 1979. Effects of humidity and moisture stress on glyphosate control of *Cyperus rotundus* L. Weed Research. 19:241-246.

Eizenberg, H., Y. Goldwasser, G. Achdary, and J. Hershenhorn. 2003. The potential of sulfosulfuron to control troublesome weeds in tomato. Weed Technol. 17:133-137.

Harrell, J. R., A. Estes, and B. McCarty. 2009. Post-emergence control on purple nutsedge. Proc. South. Weed Sci. Soc. 62:407.

Hart, S. and P. McCullough. 2009. New herbicides control yellow nutsedge in cool-season turf, Golf Course Manage. Pp. 112-115.

Holm, L.G., D. L. Plucknett, J. V. Pancho, and J. P. Herberger. 1977. The World's Worst Weeds; Distribution and Biology. Honolulu, Hawaii. University of Hawaii Press.

Hudetz, M., W. Foery, J. Wells, and J. E. Soares. 2000. CGA-362622, a new low rate Novartis post-emergent herbicide for cotton and sugarcane. Proc. South. Weed Sci. Soc. 53:163-165.

Lycan, D.W. and S.E. Hart. 2004. Relative tolerance of four cool-season turfgrass species to sulfosulfuron. Weed Technol. 18:977-981.

Martinez-Ochoa, N., S. W. Mullis, and A. S. Csinos. 2004. First report of yellow nutsedge (*Cyperus esculentus*) and purple nutsedge (*C. rotundus*) in Georgia naturally infected with Impatiens necrotic spot virus (INSV). Plant Dis. 88:771.

McCarty, L. B., J. W. Everest, D. W. Hall, T. R. Murphy, F. Yelverton. 2008. Color Atlas of Turfgrass Weeds. Second ed. Hoboken, New Jersey: John Wiley & Sons, Inc.

McElroy, J.S., F. H. Yelverton, M. G. Burton, and H. D. Cummings. 2002. Spatial distribution of Kyllinga spp. in golf course fairways. Proc. South. Weed Sci. Soc. 55:207.

McElroy, J. S., F. H. Yelverton, S. C. Troxler, and J. W. Wilcut. 2003. Selective exposure of yellow and purple nutsedge to CGA-362622, imazaquin, and MSMA. Weed Technol. 17:554-559.

McElroy, J. S., F. H. Yelverton, T. W. Gannon, and J. W. Wilcut. 2004. Foliar vs. soil exposure of green kyllinga (*Kyllinga brevifolia*) and false-green kyllinga (*Kyllinga gracillima*) to postemergence treatments of CGA-362622, halosulfuron, imazaquin, and MSMA. Weed Technol. 18:145-151.

McElroy, J. S., F. H. Yelverton, and L. S. Warren. 2005a. Control of green and false-green kyllinga (*Kyllinga brevifolia* and *K. gracillima*) in golf course fairways and roughs. Weed Technol. 19:824-829.

McElroy, J. S., F. H. Yelverton, M. G. Burton, and C. Brownie. 2005b. Habitat delineation of green and false-green kyllinga in turfgrass systems and interrelationship of elevation and edaphic factors. Weed Sci. 53:620-630.

Murphy, T. R., L. B. McCarty, D. Hall, D. L. Colvin, R. Dickens, and J. W. Everest. 1992. Weeds of southern turfgrasses. Gainesville, FL: Florida Coop. Ext. Serv. 208 p.

Nandihalli, U. B. and L. E. Bendixen. 1988. Toxicity and site of uptake of soil-applied imazaquin in yellow and purple nutsedge (*Cyperus esculentus* and *C. rotundus*). Weed Sci. 36:411-416.

Porterfield, D., J. W. Wilcut, and S. D. Askew. 2002. Weed management with CGA-362622, fluometuron, and prometryn in cotton. Weed Sci. 50:642-647.

Reddy, K. N. and L. E. Bendixen. 1988. Toxicity, absorption, translocation, and metabolism of foliar-applied chlorimuron in yellow and purple nutsedge (*Cyperus esculentus* and *C. rotundus*). Weed Sci. 36:707-712.

Richburg, III, J. S., J. W. Wilcut, and G. R. Wehtje. 1993. Toxicity of imazethapyr to purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*). Weed Technol. 7:900-905.

Richburg, III, J. S., J. W. Wilcut, G. R. Wehtje. 1994. Toxicity of AC 263,222 to purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*). Weed Sci. 42:398-402.

SAS Institute Inc. 2010. SAS version 9.2. Cary, NC.

Senseman, S. A. Ed. 2007. Herbicide Handbook. 9th Edition. Weed Science Society of America, 458 pp.

Steele, R. G. D., J. H. Torrie, and D. A. Dickey. 1997. Principles and procedures of statistics: A Biometrical Approach. 3rd ed. New York: McGraw-Hill.

Stoller, E. W. and R. D. Sweet. 1987. Biology and life cycle of purple and yellow nutsedges (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:66-73.

Stoller, E. W., D. P. Nema, and V. M. Bhan. 1972. Yellow nutsedge tuber germination and seedling development. Weed Sci. 20:93-97.

Summerlin, J. R. 1997. Biological response of six sedge species to various mowing heights. M.S. thesis. North Carolina State University, Raleigh, NC. 71 p.

Summerlin, Jr., J. R., H. D. Coble, F. H. Yelverton. 2000. Effect of mowing on perennial sedges. Weed Sci. 48:501-507.

Teuton, T. C., B. J. Brecke, J. B. Unruh, G. E. MacDonald, and J. A. Treadway. 2001. CGA-362622 for perennial weed management in warm season turfgrasses. Proc. South. Weed Sci. Soc. 54:69.

Thomas, W. E., S. C. Troxler, W. D. Smith, L. R. Fisher, and J. W. Wilcut. 2005. Uptake, translocation, and metabolism of sulfentrazone in peanut, prickly sida (*Sida spinosa*), and pitted morningglory (*Ipomoea lacunosa*). Weed Sci. 53:446-450.

Vencill, W. K., J. S. Richburg, III, J. W. Wilcut, and L. R. Hauf. 1995. Effect of MON-12037 on purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*). Weed Technol. 9:148-152.

Wehtje, G. R., R. H. Walker, T. L. Grey, and H. G. Hancock. 1997. Response of purple (*Cyperus rotundus*) and yellow nutsedges (*C. esculentus*) to selective placement of sulfentrazone. Weed Sci. 45:382-387.

Wells, J. W., M Hudetz, J. C. Holloway, Jr., E. K. Rawls, P.C. Forster, and C.L. Dunne. 2000. Introduction to CGA-362622: A new postemergence herbicide from Novartis. Proc. Beltwide Cotton Conf. 24:1459.

Wilcut, J. W. 1998. Influence of pyrithiobac sodium on purple (Cyperus rotundus) and yellow nutsedge (*C. esculentus*). Weed Sci. 46:111-115.

Wills, G. D. 1987. Description of purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*). Weed Technol. 1:2-9.

Williams, W. A, G. R. Wehtje, and R. H. Walker. 2001. Phytotoxicity of CGA-362622 and quinclorac on torpedograss (*Panicum repens*) with root versus foliar exposure. Proc. South. Weed Sci. Soc. 54:197.

Willis, J.B., D.B. Ricker, S.D. Askew. 2007. Sulfonylurea herbicides applied during early establishment of seeded bermudagrass. Weed Technol. 21:1035-1038.

Yelverton F. 1996. Know Your Sedges, Golf Course Manage. pp. 56-60.

Yelverton, F. H., T. W. Gannon, and J. D. Hinton. 2002. Control of VA buttonweed and purple nutsedge in bermudagrass with CGA-362622. Proc. South. Weed Sci. Soc. 55:51.

Yelverton, F. 2008. 2008 NCSU Turfgrass and Pasture Weed Control and PGR Annual Report, North Carolina State University. http://www.turffiles.ncsu.edu/Reports/Herbicide-PGR.aspx#004980 Accessed December 23 2010.

Table 1. Influence of herbicide and species on shoot number, shoot weight, and root weight reduction 60 DAT.[a]

Species	Shoot number reduction[b]			Shoot weight reduction[c]			Root weight reduction[d]		
	Sulfent	Sulfo	Trifloxy	Sulfent	Sulfo	Trifloxy	Sulfent	Sulfo	Trifloxy
	%								
CYPES	72	39	82	77	55	86	75	49	71
CYPRO	32	75	76	52	83	85	51	77	79
KYLGR	64	75	82	64	77	78	56	73	81
$LSD_{0.05}$	18	23	NS	16	14	NS	18	11	9

[a] Abbreviations: DAT, days after treatment; Sulfent, Sulfentrazone; Sulfo, Sulfosulfuron; Trifloxy, Trifloxysulfuron; CYPES, yellow nutsedge; CYPRO, purple nutsedge; KYLGR, false-green kyllinga.

[b] Percent shoot number reduction, relative to the nontreated.

[c] Percent shoot weight reduction, relative to the nontreated.

[d] Percent root weight reduction, relative to the nontreated.

Table 2. Influence of herbicide and placement on shoot number, shoot weight, and root weight reduction 60 DAT.[a]

	Shoot number reduction[b]			Shoot weight reduction[c]			Root weight reduction[d]		
Placement	Sulfent	Sulfo	Trifloxy	Sulfent	Sulfo	Trifloxy	Sulfent	Sulfo	Trifloxy
	%								
Soil	95	85	99	95	93	100	92	77	86
Foliar	5	12	42	14	23	48	9	44	59
Soil+foliar	66	92	98	83	98	100	83	78	86
$LSD_{0.05}$	17	22	14	15	14	14	18	11	10

[a] Abbreviations: DAT, days after treatment; Sulfent, Sulfentrazone; Sulfo, Sulfosulfuron; Trifloxy, Trifloxysulfuron.

[b] Percent shoot number reduction, relative to the nontreated.

[c] Percent shoot weight reduction, relative to the nontreated.

[d] Percent root weight reduction, relative to the nontreated.

Table 3. Influence of herbicide placement and species on shoot number, shoot weight, and root weight reduction, 60 DAT.[a]

Species	Shoot number reduction[b]			Shoot weight reduction[c]			Root weight reduction[d]		
	Soil	Foliar	Soil+foliar	Soil	Foliar	Soil+foliar	Soil	Foliar	Soil+foliar
	%								
CYPES	87	10	95	93	26	99	76	43	76
CYPRO	94	21	65	95	37	85	87	43	77
KYLGR	97	27	97	99	21	98	91	26	92
$LSD_{0.05}$	NS	NS	12	NS	NS	8	7	NS	10

[a] Abbreviations: DAT, days after treatment; CYPES, yellow nutsedge; CYPRO, purple nutsedge; KYLGR, false-green kyllinga.

[b] Percent shoot number reduction, relative to the nontreated.

[c] Percent shoot weight reduction, relative to the nontreated.

[d] Percent root weight reduction, relative to the nontreated.