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Symposium

Introduction to the Symposium: History of Sulfonylurea Herbicide Use in Turfgrass Environments

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Weed management is a common practice in golf courses, home lawns, and sod production systems. Sulfonylurea (SU) herbicides were initially introduced in the agricultural market in 1982; however, SUs were also evaluated for control of weeds and overseeded grasses. Later, SUs were evaluated for selective control of broadleaf weeds, sedges, and kyllinga species in cool- and warm-season turfgrasses. In the 1990s, chlorsulfuron and metsulfuron were registered for selective control of broadleaf weeds, such as wild garlic, spotted spurge, and difficult-to-control grasses, such as bahiagrass in turfgrass. Now, there are several SUs registered for specific weed management in both cool- and warm-season turfgrasses. The current status of SUs, along with potential benefits and drawbacks in using these herbicides for weed management practices, are discussed. The research findings, possible recommendations in relation to the safety of turfgrass (established and overseeding stands), environmental concerns (persistence and lateral movement), and management practices in cool- and warm-season turfgrasses are discussed, including the potential evolution of weed resistance.
Nomenclature: Chlorsulfuron; metsulfuron; bahiagrass, *Paspalum notatum* Fluggé; spotted spurge, *Chamaesyce maculata* (L.) Small; wild garlic, *Allium vineale* L.
Key words: History of sulfonylureas, kyllinga control, management, resistance, sedge control.

El manejo de malezas es una práctica común en campos de golf, en jardines residenciales y en los sistemas de producción de césped. Los herbicidas sulfonylurea (SU) fueron inicialmente introducidos al mercado agrícola en 1982. Más tarde, los Sus fueron evaluados para el control selectivo de malezas de hoja ancha y ciperáceas incluyendo especies *Kyllinga* en céspedes de estaciones frías y cálidas. En los 1990's el chlorsulfuron y el metsulfuron fueron introducidos al mercado de los céspedes para el control selectivo de malezas de hoja ancha y gramíneas difíciles de controlar, incluyendo *Allium vineale, Chamaesyce humistrata* y *Paspalum notatum.* Desde entonces, varios nuevos herbicidas sulfonylurea fueron introducidos para propósitos específicos en el manejo de malezas en céspedes de estaciones frías y cálidas. La situación actual de los SUs, junto con los beneficios y desventajas potenciales del uso de estos herbicidas para las prácticas de manejo de malezas son discutidos en el presente trabajo. Así mismo se discuten los resultados de investigación, posibles recomendaciones en relación a la seguridad de los céspedes (ya sea establecidos o resembrados), preocupaciones ambientales (persistencia y movimiento lateral) y las prácticas de manejo en céspedes de estaciones frías y cálidas, incluyendo el potencial de evolución de resistencia de las malezas a herbicidas SU.

Weed management is a science-based, decision-making process that includes knowledge of weed biology, environmental information, and available technology to maintain the quality of turfgrass species. This approach can lead to the least possible risks to people and the environment. The uses of sulfonylurea (SU) herbicides are common in agricultural crops and in golf courses, home lawns, and sod production. Since the mid-1970s, many SUs have been synthesized, and their herbicidal activities established. Since then, several SUs have been registered for use in the agrichemical market. Because of the great number of potential active ingredients from this class and the relatively short patent periods (17 yr), companies have continued to work with this class of chemistry and have released new herbicides for use in various cropping systems.

The herbicidal properties of SUs were first reported in 1966 (Koog 1966). The early SUs were derivatives of triazine herbicides. George Levitt of E. I. Du Pont de Nemours and Company noted that the SUs having an aniline as the aryl group exhibited weak plant-growth regulatory activity, whereas the aminopyrimidine derivatives displayed very high biological activity (Levitt 1983; Sauers and Levitt 1984). Levitt (1983) soon produced SUs having conventional herbicidal activity and, thus, began one of the most exciting breakthroughs in the field of herbicide research, representing a major development in the pesticide industry. In 1989, there were 375 patents issued to 27 agrochemical companies covering tens of millions of suspected biologically active structural variations (Brown 1990). In 2002, there were 27 SUs listed in the Weed Science Society of America *Herbicide Handbook* (Vencill 2002), which was the largest number of herbicides for any chemical family (Waltz and Murphy 2004). Interestingly, only 17 of those herbicides were labeled for use in North America, but since the printing of that publication, several SUs (ethoxysulfuron, flazasulfuron, iodosulfuron, and foramsulfuron) have been registered.

The SU herbicides are not new to the turfgrass market. Metsulfuron and sulfometuron have been used since the 1980s for broad-spectrum weed control in cool- and warm-season turfgrasses (Table 1). Although the older SUs were broader in the number and type of weeds controlled, the

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Table 1. Chemical and common names of sulfonylurea herbicides used in turfgrass environments.

Chemical name	Common name	Common uses
Metsulfuron	Manor or Blade	Chickweed, bittercress, white clover, dandelion, ground ivy, spotted spurge; grass and sedge species
Chlorsulfuron	Corsair	Broadleaf species and grasses
Ethoxysulfuron	Sunrice	Sedge species and kyllinga species; some broadleaf species
Foramsulfuron	Revolver	Broadleaf species and grasses
Halosulfuron	Sedgehammer formerly known as Manage)	Grass and sedge species
Rimsulfuron	TranXit GTA	Broadleaf; grass and sedge species
Trifloxysulfuron	Monument	Broadleaf; grass and sedge species
Flazasulfuron	Katana	Grass and sedge species
Sulfosulfuron	Certainty	Buttercup, chickweed, white clover, dandelion; grass and sedge species
Iodosulfuron	Component of Celsius	Broadleaf; grass species

newer SUs are more weed specific, with minimal to no phytotoxicity on tolerant turfgrass species. As an example, halosulfuron is very effective at controlling problematic sedges, like purple nutsedge (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.), and kyllinga species, like green kyllinga (*Kyllinga brevifolia* Rottb.) and false green kyllinga (*Kyllinga gracillima* Miq.), but does not injure cool- and warm-season turfgrasses.

The herbicidal activity of SUs is characterized by high biological activity on susceptible weeds, short half-lives, and low toxicities to animal species (Brown 1990). The high biological activity is the reason for the low use rates associated with this chemistry, which has several advantages, such as reducing the amount of active ingredient applied to the environment and reducing handling and container disposal issues (Brown 1990; Mitra et al. 2007; Senseman 2007). An example of this is the use of halosulfuron for the control of nutsedge, compared with the traditional use of MSMA. In a single year, if one application of halosulfuron was applied at the high label rate (150 g ai ha^{-1}), it would take more than 15 yr to equal the amount of active ingredient from one application of MSMA (2.2 kg ai ha^{-1}). In fact, often, two to five annual applications are needed for effective control of sedge species with MSMA. SUs offer a distinct advantage over many other herbicides, such as MSMA, because effective, weed-specific control can be achieved with "fewer pounds on the ground."

The highly versatile SUs provide golf course superintendents and professional turf managers with tools to control weeds in cool- and warm-season turfgrasses, such as perennial ryegrass (*Lolium perenne* L.) or roughstalk bluegrass (*Poa trivialis* L.), in fall, or they can be used during spring transition to remove the cool-season turfgrasses. Several SUs have been registered for use on golf courses and sports turf facilities.

Behavior of SUs in Plants

Several SU herbicides have been introduced into the turfgrass market for selective control of broadleaf weeds; difficult-to-control grasses, like annual bluegrass (*Poa annua* L.), roughstalk bluegrass, "clumpy" perennial ryegrass, and creeping bentgrass (*Agrostis stolonifera* L.), and sedges like yellow nutsedge, purple nutsedge, green kyllinga, and false green kyllinga.

Mode of Action. Herbicides of this family are absorbed by foliage and roots and inhibit growth at both locations (shoot and root). Once absorbed into the plant, SUs are rapidly translocated acropetally from the root to the shoot and basipetally from the shoot to the root in the xylem and phloem to areas of active growth.

Research has shown that SUs work by inhibiting the plant-specific enzyme acetolactate synthase (ALS), which is required for the biosynthesis of branched-chain amino acids. The branched-chain amino acids valine, leucine, and isoleucine are required components for growth processes and cell division. By blocking ALS and preventing branched-chain amino acid production, SU herbicides rapidly inhibit cell division at the root and shoot tips. Studies detected cell division inhibition as quickly as 1 to 2 h after application (Brown 1990). However, whole-plant symptoms, such as vein reddening, leaf chlorosis, and terminal bud death were not evident for several days. Usually 1 to 3 wk are required from the time of application to complete control of the target weed.

Selectivity. All plants have the enzyme ALS, but not all plants are susceptible to injury from SUs. Differential susceptibility may be caused by of several factors, including (1) differential uptake or translocation or both, (2) differential active-site sensitivity, and (3) metabolic inactivation by the tolerant plant.

Because SUs are target-site specific, differential active-site sensitivity is not the reason some plants are tolerant and others are not. Most plant physiologists agree that metabolic inactivation, where one plant can inactivate or breakdown the herbicide more quickly than another, is most likely the primary means of selectivity. Tolerant plant species have been shown to metabolize an applied SU in 4 to 6 h, whereas sensitive species and weedy species have internal plant half-lives of more than 50 h (Brown 1990).

Toxicology. SU herbicides act upon a specific plant enzyme (ALS), which is not found in mammals or other animals (Brown 1990). For that reason, SUs have very low acute and chronic toxicity. Therefore, they are considered essentially nontoxic to animals.

Behavior of SUs in Soil

SU herbicides tend to move laterally, so application of SUs in saturated soils should be avoided. To reduce lateral movement, a short irrigation (about 0.6 cm [0.24 in]) can be used after SU herbicide application (Yelverton 2004). Hydrolysis of SUs leads to degradation of the parent herbicide molecule, which is favored under acidic soil pH conditions, as compared with neutral and basic soil pH (Sarmah et al. 2000).

Soil persistence. Under acidic soil conditions, the half-life of herbicides in this family typically ranges from 4 to 56 d, with an average of 35 d (Senseman 2007). SU herbicides are degraded by chemical hydrolysis and microbial breakdown, and both processes are accelerated under acidic conditions. In addition, water and soil pH influences the water solubility, sorption to organic matter, and soil mobility of SUs, which have relatively low organic carbon partition coefficient (K_{oc})(Waltz and Murphy 2004). The K_{oc} value is a measure of a chemical's affinity for the organic carbon component of the soil. A chemical with a high K_{oc} has greater affinity for adsorption to soil, i.e., the greater the K_{oc}, the greater the SU herbicide soil adsorption. Photodegradation has little effect on this class of herbicides.

At neutral and alkaline conditions, some SUs may persist for 2 yr, which may influence the planting of various plant species. Many of the SUs have herbicidal activity on cool-season turfgrass species, like the perennial ryegrass, commonly used as an overseeding species on bermudagrass [*Cynodon dactylon* (L.) Pers.] tees, fairways, and greens. However, SUs that have short soil half-lives, such as foramsulfuron and rimsulfuron, can be applied for annual bluegrass control 14 d before ryegrass overseeding.

More-detailed information on SU fate in the soil is presented in this symposium series by Grey and MCollough.

Broadleaf Weed Control in Cool-Season Turfgrass

Limited information on the activity of SU herbicides on broadleaf weeds in cool-season turfgrasses is available. More information on broadleaf weed control is presented in this symposium series by Derr.

Cool-Season Grass Removal for Bermudagrass Spring Transition

The SUs provide superintendents with tools to control weeds before overseeding warm-season turfgrasses and controlling cool-season turfgrasses during spring transition (Mitra 2005; Mitra et al. 2007; Umeda and Towers 2004; Yelverton 2003). They can be used during spring transition to remove the cool-season turfgrasses. More-detailed information on spring transition is presented in this symposium series by K. Umeda.

SUs for Sedge and Kyllinga Control

Nutsedge (*Cyperus* L.) species and kyllinga (*Kyllinga* Rottb.) species are common, rapidly spreading, perennial weed species in turfgrass environments that prefer above-normal soil moisture (Bendixen and Nandihalli 1987; Bryson et al. 1997). Research has also indicated that sedge species incidence in turfgrass systems has increased in recent years, likely due, in part, to changes in herbicide programs (Yelverton 1996). Although purple nutsedge is not as widely distributed as other nutsedge species, it has been described as "the world's worst weed" because it is a serious competitor with more crops that any other weed in the world (Holm et al. 1977; Tucker 1987).

Sulfosulfuron was developed for POST weed control in wheat (*Triticum aestivum* L.), sedge control in warm-season turfgrasses (Senseman 2007), and sedge control in selected cool-season turfgrasses (Bhowmik et al. 2006).

As an alternative to MSMA, SUs offer a distinct advantage with effective, weed-specific control. Some SU herbicides, such as halosulfuron, can be used selectively for POST control of sedges in cool-season turfgrasses (Bhowmik and Sarkar 2008; Bhowmik et al. 2006), whereas some SUs, such as trifloxysulfuron, can control sedges only in warm-season turfgrasses (Yelverton 2004).

In recent years, kyllinga species are becoming more prevalent in golf courses, and they are spreading rapidly northward and westward from their original geographic distribution (Bhowmik and Sarkar 2009). Whole plants or fragments of the perennial kyllinga species spread as contaminants in transported turfgrass sods and sprigs (Yelverton 1996). Frequent irrigation, and higher mowing frequency without removal of clippings around golf course greens, enhances vegetative reproduction of kyllinga species.

Trifloxysulfuron is another SU herbicide currently registered for POST weed control in cotton (*Gossypium hirsutum* L.), sugarcane (*Saccharumofficinarum* L.), and select warm-season turfgrasses (Brecke and Unruh 2000; Porterfield et al. 2002). In general, flazasulfuron, halosulfuron, sulfosulfuron, and trifloxysulfuron were registered for excellent control of false green kyllinga (Bhowmik 2010; Yelverton 2004).

Field trials have been conducted to evaluate sulfosulfuron and trifloxysulfuron for POST control of false green kyllinga (Bhowmik 2010; Yelverton 2004), yellow nutsedge (Bhowmik et al. 2006), and purple nutsedge (Yelverton 2004). Sulfosulfuron (66 g ai ha^{-1} followed by [fb] 66 g ai ha^{-1}) and trifloxysulfuron (28 g ai ha^{-1} fb 28 g ai ha^{-1}) provided greater than 80% false green kyllinga and purple nutsedge control. Application volume did not influence the efficacy of sulfosulfuron, halosulfuron, and ethoxysulfuron treatments (Bhowmik 2010). These data indicate sulfosulfuron and trifloxysulfuron may offer effective sedge control in turfgrass environments.

Potential Evolution of SU Resistance and Methods to Prevent Resistance

SU herbicides have been used in agricultural crops for more than 25 yr, and numerous weed species have been reported to have developed resistance to these ALS-inhibiting herbicides (SUs and imidazolinone). Resistance has been reported after repeated use of chlorsulfuron and metsulfuron in cereal production (Brown 1990) and with sulfometuron for Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] control. Rigid ryegrass (*Lolium rigidum* Gaudin) has been reported to be resistant to ALS-inhibiting herbicides, which might involve two mechanisms: enhanced metabolism of the herbicides or an herbicide-insensitive ALS enzyme or both

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(Christopher et al. 1992). Hence, care should be taken to rotate SU herbicides with herbicides that have different modes of action.

Detailed information on potential weed resistance to SUs is presented in this symposium series by Golembiewski and Mallory-Smith.

Future Uses of SUs

Several SUs are being introduced into the turf market for selective control of broadleaf weeds; difficult-to-control grasses, like annual bluegrass, ''clumpy'' perennial ryegrass, and creeping bentgrass; and sedges, such as yellow nutsedge, purple nutsedge, and green and false green kyllinga and other kyllinga species. There are limited problems associated with SU herbicide uses. However, potential issues include (1) increasing the ability to selectively control one turfgrass species in another turfgrass species, (2) increasing the broad spectrum activity of SUs on weed species, (3) increasing turfgrass safety, (4) reducing lateral movement or leaching by encapsulation of SUs, (5) reducing the ''tracking'' of SUs, (6) extending soil persistence for long-term weed control, and (7) preventing or extending the time before weed resistance to SUs.

In conclusion, the SU herbicides will continue to provide superintendents with tools to control weeds before overseeding with warm-season turfgrasses and to control cool-season turfgrasses during spring transition. Some SUs, such as halosulfuron or sulfosulfuron, can be used to selectively control sedges in cool-season turfgrasses, whereas others, such as trifloxysulfuron, can control sedges only in warm-season turfgrasses. SUs will continue to be developed for turfgrass weed management.

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