USE OF HERBICIDES ON TURFGRASS[1]

Uso de herbicidas em gramados

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ABSTRACT - In crop production, weeds must be controlled so as not to adversely affect crop yield and crop quality. Thus, a low level of weeds infesting a field, in most instances, is not a problem. Except in sod or seed production, turfgrass does not have a yield component. The value of turfgrass is its inherent aesthetic quality and usability. Aesthetic quality is the beauty and value that turfgrass adds to a managed landscape. Usability can be the durability of a sport field, trueness of golf putting green roll, or reduction in soil loss from water runoff or wind. Any weed presence in turfgrass can decrease the aesthetic quality and usability of turfgrass. Utilizing herbicides is the only way to completely control weeds in a turfgrass stand. While it is possible to reduce weed populations using cultural or mechanical management practices, it is impossible to completely eliminate weeds as can be accomplished with herbicides. This manuscript will review the major herbicides used in turfgrass in the United States with respect to their modes of action, herbicide family, and primary use in turfgrass.

Keywords: preemergence, postemergence, selectivity, chemical control, weed.

RESUMO - Nas culturas agrícolas as plantas daninhas devem ser controladas de modo a não afetar negativamente o rendimento e a qualidade do produto colhido. Deste modo, quantidades pequenas de plantas daninhas em um campo, na maioria dos casos, não é um problema, exceto na produção de sementes. Ressalta-se que em gramados não existe um componente de produção a se colhido. O valor do gramado é a sua qualidade inerente a estética e usabilidade. Qualidade estética é a beleza e o valor que acrescenta ao gramado em uma paisagem gerenciada. Usabilidade pode ser a durabilidade de um campo de esporte ou a redução na perda de solo pela erosão da água ou do vento. A presença de qualquer planta daninha em gramados pode diminuir a qualidade estética e usabilidade do gramado. Enquanto for possível reduzir a população de plantas daninhas utilizando práticas culturais ou mecânicas, não se poderá eliminá-las completamente. A utilização de herbicidas é a única maneira de controlar completamente as plantas daninhas em áreas de gramados. Esta revisão irá rever os principais herbicidas utilizados em gramados nos Estados Unidos com relação a seus modos de ação, a família de herbicidas e uso primário no gramado.

Palavras-chave: pré-emergência, pós-emergência, seletividade, controle químico, plantas daninhas.

INTRODUCTION

Weeds decrease the aesthetic value and the usability of turfgrass. In residential or commercials lawns, weed-free turf increases property value and business attractiveness. In sports turf, weeds are less wear tolerant which can be reduced to bare ground faster than more wear tolerant turfgrass species. On golf courses, weeds infesting putting greens can reduce putting trueness that increases the unpredictability of an already difficult game. In parks and city common areas, the ephemeral nature of weeds can lead to seasonal erosion and decrease the usability of public spaces. The same is true for roadsides

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and turfgrass planted for erosion control. Weed species simply cannot maintain a contiguous surface to prevent soil loss like adapted turfgrass species.

It is commonly said "Only bad turf leads to weed infestations". This means that if one maintains optimum growing conditions for turfgrass fertility, irrigation, drainage, light quality and quantity the one will simply have weed-free turfgrass. Such logic is totally and completely false. Weeds, of all situations, are adapted for not only bad agronomic conditions, but they are also adapted to thrive under excellent agronomic conditions (Busey, 2003). Changing agronomic practices to reduce the competitiveness of one weed simply shifts the weed problem to another species. It is because of the omnipresent nature of weeds that herbicides are used.

Herbicides are a vital and necessary component for turfgrass weed management. Herbicides are primarily classified in two ways, first by chemistry and then by use (Senseman, 2007). Herbicide classification by chemistry organizes herbicides according to mode of action and family. A mode of action is the physiological or biochemical mechanismby which a herbicide kills or injures plants (Senseman, 2007). Herbicides are quite diverse in their modes of action and specificity, as will be discussed throughout this manuscript. A herbicide family is a group of herbicides based on their chemical structure (Senseman, 2007). Normally, members of a herbicide family also will have the same mode of action; however there are exceptions to this rule. Diuron for example, inhibits root development, but is classified in the substituted urea family based on chemistry, which inhibit photosystem II electron transport (Senseman, 2007). Also, it's not uncommon that several herbicide families be classified in the same mode of action. For the purpose of this review, we will only be covering mode of action and herbicide family in order to discuss the third way of classifying herbicide classification by how the herbicides are used.

Classification of herbicide by use first begins with the crop in question, which in this case is turfgrass. Herbicides are known to affect turfgrasses differently due to the fact that turfgrasses themselves are a diverse assortment of grasses (Table 1). Distinct difference can be drawn with respect to simply classifying turfgrasses into warm and cool season turfgrass groups. In general, cool-season turfgrasses (turfgrasses adapted to frozen snow-covered winter conditions) are more tolerant of ACCase herbicides and less tolerant of ALS inhibiting herbicides (Dernoeden, 1987). Warm-season turfgrasses (turfgrasses adapted to frost or infrequent snow induced dormancy conditions or warmer climates) are less tolerant of ACCase inhibiting herbicides and more tolerant of ALS-inhibiting herbicides (McElroy & Breeden, 2006). Exceptions to this rule exists of course, the most notable being that of zoysiagrass which tolerant to both groups of herbicides (McElroy & Breeden, 2006; Lewis, et al. 2010).

The second step in classifying herbicides by how they are used is by weeds controlled. Herbicides can be either selective (not all plants are killed or injured) or non-selective (all plants are killed or injured) (Senseman, 2007). With respect to selective herbicides, there are four main groups of weeds that are targeted by herbicides: broadleaf (dicots), grasses (monocots), sedges (monocots), and other non-grass monocots (McElroy & Bhowmik, 2013). Broadleaf weeds are the easiest weeds to control in turfgrass due to the apparent physiological and biochemical differences that occur between dicots and monocots. Granted, not all herbicides are equally effective on all broadleaf weeds, but through the combination of numerous prepackaged herbicides (e.g. Trimec, a prepackaged mixture of 2,4-D, dicamba, and MCPP) broad-spectrum broadleaf weed control can be achieved in any turfgrass species. Further, control of sedges and other non-grass monocots can be controlled selectively in turfgrass due to the apparent herbicide response differences. It is far more difficult to achieve selectivity when the goal is to control a grass weed in a grass crop, whether it is corn (*Zea mays*) or turfgrass species (Dobbels & Kapusta, 1993; Beam et al., 2006). Herbicide response differences have been discovered between C_3 and C_4 species, but there are few herbicide options when attempting to selectively control C_3 or C_4 weeds in C_3 or C_4 turfgrass, respectively.

Table 1 - A list of common turfgrass species and cultivars

Seasonality	Common name	Scientific name	Common cultivars
Warm-season	bermudagrass	*Cynodon dactylon*, *Cynodon dactylon* x *Cynodon transvaalensis*	TifWay, TifSport, Patriot, TifDwarf, TifEagle, MiniVerde, Champion
	zoysiagrass	*Zoysia matrella*, *Zoysia tenuifolia, Zoysia japonica*	Emerald, Meyer, Diamond, Zeon, Zorro, Zenith
	centipedegrass	*Eremochloa ophiuroides*	common, TifBlair
	St. Augustinegrass	*Stenotaphrum secundatum*	Raleigh, Palmetto, Seville, Floratine, Florastam
	seashore paspalum	*Paspalum vaginatum*	Salam, Seadwarf, Sea Isle
Cool-season	tall festuce	*Festuca arundinacea*	>100
	perennial ryegrass	*Lolium perenne*	>100
	creeping bentgrass	*Agrostis palustris*, *Agrostis stolonifera*	Crenshaw, Penncross, A1, G2, many others
	Kentucky luegrass	*Poa pratensis*	>100
	fine fescue	*Festuca tenuifolia* (often includes *Festuca ovian* and *Festuca rubra*)	>100

Preemergence herbicides

Preemergence herbicides are the most commonly used herbicides used in turfgrass (McElroy & Bhowmik, 2013). Preemergence herbicides are applied to prevent the establishment weeds by controlling weeds at germination. Preemergence herbicides must be applied in a timely fashion prior to weed seed germination (Senseman, 2007). There are two normal timings for preemergence weed control applied in late winter to early spring to control summer annual weeds or applied in late summer to early autumn to prevent the emergence of winter annual weeds. In both cases, preemergence herbicides can be applied as a single large dose or as two sequential applications (Dernoeden, 2001). The concern in both application scenarios is to provide a continual herbicide barrier at the soil surface that can continue to control germinating weed seed.

It is a common misconception that preemergence herbicides prevent weed seed germination. In fact, preemergence herbicides act by preventing root and/or shoot development after germination occurs (Senseman, 2007). There are three preemergence herbicide modes of action: mitotic inhibitors, protox inhibitors, and cellulose biosynthesis inhibitors.

Mitotic inhibiting herbicides include the dinitroaniline and pyrimidine herbicide families (Senseman, 2007). The dinitroaniline family used in turfgrass includes prodiamine, pendimethalin, oryzalin, benefin, and trifluralin. Dinitroanilines are preemergence herbicides that selectively control germinating grasses and small-seeded broadleaf weeds by arresting cell division through inhibition of spindle fiber formation (Parka & Soper, 1977). Dinitroaniline herbicides are yellow to orange in color, are prone to stain equipment and clothing. These herbicides can be formulated for spray applications or granular spread applications. In both cases, these herbicides must be watered in soon after application to prevent volatility loss. Dinitroanilines have no postemergence activity.

The pyrimidine family contains several herbicides that are classified as auxin mimics (to be discussed later) but only one herbicide that inhibits mitosis dithiopyr. While both dinitroaniline herbicides and dithiopyr both inhibit mitosis, dithiopyr does so in a slightly different fashion (Cutulle et al., 2009). Unlike dinitroanilines, dithiopyr has preemergence activity and postemergence activity on certain weeds- primarily *Digitaria* spp. (Reicher et al, 1999). Further, dithiopyr can also be formulated for granular or liquid application but it less likely to be lost due to volatility. Dithiopyr is generally considered less consistent for preemergence *Digitaria* spp. control compared to prodiamine (Johnson 1996). Dithiopyr should normally only be applied for control of

Digitaria spp. that are one tiller or less in size due to decreasing activity as plant size increases (Johnson, 1997). Both Dithiopyr and dintroaniline herbicides have limited leaching potential in soil, thus they are typically found in the turfgrass thatch layer or top 5 cm of soil (Schleicher et al., 1995).

Protox-inhibiting herbicides are a second mode of action that function as preemergence herbicides. Protox or protoporphyrinogen IX oxidase catalyzes the conversion of protoporphyrinogen IX to protoporphyrin IX PPIX (Duke et al, 1991). PPIX formed outside of thylakoids absobs light and reacts with oxygen species forming free radicals that degrade cellular structures (Duke et al., 1991; Senseman, 2007). Oxadiazon is protox-inhibiting herbicide in the oxadizole family specifically formulated for preemergence weed control in turfgrass (Matringe et al., 1989; Duke et al., 1991; Senseman, 2007). Oxadiazon is formulated as a granular or liquid formulation. Granular formulations are most commonly applied because even though oxadiazon is marketed and sold as a preemergence herbicide, oxadiazon also has non-selective postemergence herbicide activity (Menges & Tamez, 1981). Oxadiazon applied as a liquid application must be made to dormant turfgrass or must be watered in within minutes after application (McElroy & Bhowmik, 2013). The most unique use of oxadiazon is that it can be applied to newly sprigged bermudagrass turf with no damage or slowing of bermudagrass development (Fagerness et al., 2002). Carfentrazone and sulfentrazone are other protox inhibiting herbicides that are used as postemergence herbicides in turfgrass. They will be discussed separately in subsequent sections.

Cellulose biosynthesis inhibiting herbicides are the final group of preemergence herbicides used in turfgrass. It should be noted that cellulose biosynthesis inhibiting herbicides is a diverse mode of action containing numerous herbicides often belonging to only one herbicide family (Sabba & Vaughn, 1999). Because of this, while these herbicides do inhibit some form of cellulose biosynthesis, their exact mechanisms of action can be quite diverse.

Two herbicides inhibiting cellulose biosynthesis are used as preemergence herbicides in turfgrass – isoxaben and indaziflam. Isoxaben inhibits cell wall biosynthesis. Weed control with isoxaben is primarily limited to preemergence broadleaf control (Derr, 2012). Preemergence control of broadleaf weeds to the exclusion of grass weeds is the opposite of dinitroaniline herbicides and dithiopyr. As such, isoxaben and preemergence herbicides that target grass weeds more effectively are often formulated together to increase the spectrum of weed control (Grant et al., 1990). These mixtures are also popular for control of container-grown ornamentals and in ornamental landscape beds (Neal & Senesac, 1990; Derr, 1994).

Indaziflam is one of the newest herbicides introduced in the turfgrass market in the United States. It is classified in the alkylazine family as a cellulose biosynthesis inhibiting herbicide, although its exact mode of action is unknown (Meyer et al., 2009; Perry et al., 2011). Indaziflam is unique because it requires a much lower use rate than traditional preemergence herbicides (approximately 30 to 50 g a.i. ha^{-1} compared to 1 to 3 kg a.i. ha^{-1}). Indaziflam also provides preemergence and early postemergence control of *Poa annua* and some *Digitaria* spp. (Perry et al., 2011; Brosnan & Breeden, 2012).

While the majority of research on turfgrass herbicides has centered around synthetic herbicides. There is one “natural” herbicide that has been specifically developed for the turfgrass market corn gluten meal. Corn gluten meal was discovered and patented at Iowa State University by Dr. Nick Christians. Corn gluten meal is a natural by-product of the corn wet-milling process (Christians, 1991; Liu & Christians, 1996). The bioactive molecule is a five amino acid chain that reduces seedling survival by inhibiting root and shoot development (Bingaman & Christians, 1995). While not as effective as traditional synthetic preemergence herbicides, corn gluten meal can reduce *Digitaria* spp. populations by 50 to 60% and is potential natural product alternative to conventional herbicides (Dernoeden, 2001). As a historical note, the herbicidal properties of corn gluten meal were accidentally discoverer by Dr. Christians as he was trying to utilize the corn gluten meal to propagate and spread turfgrass fungal diseases as a means to inoculate uniform disease pressure for fungicide testing (Nick Christians, personal communication). The discovery of the herbicidal properties is a case of careful observation of all possible outcomes.

The auxin mimics

Herbicides classified as having a mode of action that induce symptomology resembling an overdose of the hormone auxin are referred to as auxin mimic herbicides (Grossman, 2010). Induction of abscisic acid biosynthesis has also been implicated as a potential factor leading to plant death (Grossman et al, 1996). Auxin mimics induce epinasitic twisting and curling of the plant foliage leading to disruption of vascular movement and eventual plant death. Interestingly, auxin mimic herbicides are primarily active on broadleaf, dicotyledonous weed species with a few exceptions. The lack of grass activity has lead to the widespread use of auxin mimic herbicides in turfgrass. In fact, the initial field experiments for 2,4-D development were conducted on a home lawn for white clover (*Trifolium repens*) control (Timmons, 1970).

There are four main herbicide families that are classified in the auxin mimic mode of action: phenoxy, benzoic acid, picolinic acid, and pyridine (Senseman, 2007). Phenoxy herbicides include 2,4-D, MCPP (also known as mecoprop), MCPA, and 2,4,5-T (banned in the United States). Dicamba is the only herbicide used in turfgrass classified as a benzoic acid. Picolinic acids include clopyralid, aminopyralid, and picloram. Pyridine herbicides include triclopyr and fluroxypyr.

Despite so many auxin mimic herbicides used in turfgrass, it is interesting to note that it is rare that a single auxin mimic be applied alone (Neal, 1990). In other words, almost all auxin mimic herbicides are applied from prepackaged mixtures. Despite the similarities between auxin mimic herbicides, there are subtleties in the different broadleaf weed that are controlled. Different turfgrass scenarios may have several species inhabiting one stand. Henbit (*Lamium amplexicaule*), common chickweed (*Stellaria media*), common dandelion (*Taraxacum officinale*) and hairy bittercress (*Cardimine hirsutum*), for example, commonly infest turfgrass during winter months. By combining two to four auxin mimic herbicides in one application greater control of these species can be achieved with little consideration to exactly which species are present.

Prepackaging of herbicide began with the combination of 2,4-D, MCPP, and dicamba. The mixture of these three herbicides are sold by the tradename "Trimec" by PBI/Gordon (St. Louis, MO, USA). Trimec has become a synonymous term for prepackaged mixtures of these herbicides with turfgrass managers often using the term "generic Trimec" for any producting containing 2,4-D, MCPP, and dicamba.

Quinclorac is classified as having two modes of action and this dual classification is still much debated (Grossman, 1998). Grossman (1998) classified quinclorac as a mimic of natural auxin due to epinastic gross morphological response and cyanide/ABA accumulation similar to other auxin mimic herbicides. Unlike other auxin mimic herbicides, quinclorac is primarily used for control of *Digitaria* spp. and torpedograss (*Panicum repens*) in turfgrass (Reicher et al, 1999; Brecke et al., 2001). Quinclorac is also effective select broadleaf weeds, including white clover (*Trifolium repens*), with a broader spectrum of control achieved by mixing with other auxin mimic herbicides (Neal & Senesac, 1993). A major weakness of quinclorac is little to no activity on goosegrass (*Eleusine indica*), which is normally targeted for control at a similar time as *Digitaria* spp. (Zawierucha et al, 2001). A great benefit of quinclorac is the ability to be used on newly seeded turfgrass species with little to no injury to the developing turfgrass (McElroy et al., 2007; McElroy & Breeden, 2007).

MSMA

MSMA, or monosodium methane arsonate, is a herbicide in the organic arsenical family with an unknown mode of action. It is utilized as a postemergence herbicide for grass, broadleaf, and sedge weed control in bermudagrass, zoysiagrass, and tall fescue- the three most widely used turfgrasses in the United States (Coats et al., 1987). Most notably, centipedegrass, St. Augustinegrass, seashore paspalum, and creeping bentgrass are easily injured by MSMA (Johnson, 1994; Johnson & Duncan, 2001). Specifically, MSMA is used to control *Digitaria* spp., *Paspalum dilatatum*, *Eleusine indica*, *Cyperus* spp., *Kyllinga* spp., and numerous broadleaf weeds (Johnson, 1975a; Johnson, 1980b; Coats et al., 1987; McElroy et al., 2004). Put simply, MSMA is one of the most widely used, low cost treatments for weed control in turfgrass in the United States. However, all organic arsenical herbicide are currently being phased out in the United States by the US Environmental Protection Agency as a means of reducing human exposure to arsenic (USEPA, 2009)

Photosystem II inhibiting herbicides

Photosystem II (PSII) inhibiting herbicides prevent the movement of electrons from through the electron transport chain at the quinone binding site of the D1 protein (Senseman, 2007; Shimabukuro & Swanson, 1969). By inhibiting electron transport, triplet state chlorophyll can then react with molecular oxygen forming oxidative free radicals. Free radicals then react with cellular constituents leading to membrane and cell wall degradation, and loss of other cellular function (Senseman, 2007). The key site of action is the competitive herbicide binding with plastoquinone (Powles & Yu, 2010). Mutations to the amino acid sequence of this binding site can lead to de novo resistance in previously controlled populations (Powles & Yu, 2010). Resistance to PSII inhibiting herbicides via the described mechanism has occurred with *Poa annua* in turfgrass (Perry et al, 2012).

Two herbicide families that inhibit PSII are commonly used in turfgrass: triazine and substituted urea. Triazine herbicides used in turfgrass are atrazine, simazine, and metribuzin. All of these herbicides are labeled only for warm-season turfgrass. Injury can occur to warm-season grass turf when treated with triazines therefore applications are limited to dormant periods or situations where injury can be tolerated. Despite these risk factors, triazine herbicides are still widely utilized. Simazine and atrazine is commonly used for weed control in dormant bermudagrass and centipedegrass turf. Both can be applied during establishment of centipedegrass from seed. Metribuzin is most commonly used for dallisgrass (*Paspalum dilatatum*) control in bermudagrass, so long as injury can be tolerated (Henry et al., 2007). Triazine herbicides are regulated in the United States due to the potential for ground water contamination (Dorfler et al., 1997).

Substituted ureas are less commonly used in turfgrass compared to triazine herbicides. Substituted urea herbicides used in turfgrass are diuron and siduron. Diuron is commonly used on roadsides or unimproved turfgrass for preemergence control of winter annual and broadleaf weeds (Johnson, 1975b). Siduron is used for preemergence crabgrass control in cool-season turfgrass and for control of bermudagrass in bentgrass putting greens (Bingham & Schmidt, 1983; McElroy & Breeden, 2006).

Protox-inhibiting herbicides

Oxadiazon (discussed previously) is a protox inhibiting herbicides primarily used asa preemergence herbicide in turfgrass. Carfentrazone and sulfentrazone are protox-inhibiting herbicides used primarily as postemergence herbicides in turfgrass (Willis et al., 2007; Brosnan et al., 2010). Carfentrazone is primarily active on broadleaf weeds and all commonly used turfgrass species are highly tolerant (McElroy & Breeden, 2007; Borst et al., 2010). Tolerance is great enough that carfentrazone can be used on newly seeded turfgrass; however, only broadleaf weeds are controlled and quinclorac or siduron must be used in conjunction to improve control (McElroy & Breeden, 2007). Carfentrazone is uniquely used for silvery-thread moss (Bryum argenteum) control in creeping bentgrass putting greens (Borst et al., 2010). Silvery-thread moss is a common bryophyte that infests closely mowed creeping bentgrass putting greens. Various fertilizer mixtures can be utilized for silvery-thread moss control with unpredictable for turfgrass injury potential (Burnell et al., 2004). Carfentrazone is the only synthetic herbicide that is registered for moss control in turfgrass and has little to no injury potential (Borst et al., 2010).

ALS-inhibiting herbicides

Acetolactate synthase inhibiting herbicides represent the largest herbicide mode of action specifically registered for turfgrass use. There are four herbicide families used in turfgrass classified as ALS inhibitors (listed in order of number of herbicides used in turfgrass): sulfonylurea, imidazolinone, triazolopyrimides, andpyrimidinyl benzoics. Sulfonylurea contains the largest number of herbicides of any herbicide family used in turfgrass. Sulfonylurea herbicides used in turfgrass are: chlorsulfuron, metsulfuron, halosulfuron, foramsulfuron, trifloxysulfuron, flazasulfuron, rimsulfuron, iodosulfuron, and sulfosulfuron. Sulfonylurea herbicides are very diverse in their activity on different weed species and turfgrass tolerance, which often is a source of confusion for both researchers and turfgrass managers alike trying to differentiate sulfonylurea herbicides based on weed and turfgrass tolerance. For instance, halosulfuron is safe across all turfgrass species, controls only sedges, and has little to no activity on broadleaf weeds (Fry et al., 1995; McElroy et al., 2004). Chlorsulfuron controls many broadleaf weeds, Poa annua, tall fescue, but is safe on warm-season turfgrasses and Kentucky bluegrass (Larocque et al., 1985; Gaul and Christians, 1998). Metsulfuron has the broadest spectrum of broadleaf weed control, but does not control sedges. Metsulfuron controls *Paspalum notatum*, but not *Paspalum dilatatum* or Seashore paspalum. Further, bermudagrass, zoysiagrass, and St. Augustinegrass are tolerant, but centipedegrass, tall fescue, Kentucky bluegrass are sensitive (Johnson, 1987).

There are five sulfuonylurea herbicides that have a similar spectrum of control except for a few exceptions: foramsulfuron, flazasulfuron, trifloxysulfuron, sulfosulfuron, and rimsulfuron. These five herbicides are safe on bermudagrass and zoysiagrass, with minor safety on other warm-season turfgrasses and these herbicides are active on almost all cool-season turfgrasses (Stephenson IV et al., 2006; Brecke et al., 2008). Sulfosulfuron is the least active on cool-season turfgrasses and has potential use for weed control in cool-season turfgrass (Lycan & Hart, 2004). Thus, these herbicides are commonly utilized in warm-season turfgrass for *Poa annua* control, with the least effective two being flazasulfuron and sulfosulfuron (Harrell et al., 2005; Toler et al., 2005). With the exception of foramsulfuron, these herbicides also control *Cyperus* and *Kyllinga* spp. (McElroy et al., 2004).

A very unique use of sulfonylurea herbicides is that of overseeding removal form bermudagrass turf. Dormant bermudagrass turfgrass is often overseeded with *Lolium perenne* and *Poa trivialis* to provide green winter color. However, if the overseeding grass is not removed in the spring it can suppress the bermudagrass turf and cause potential damage in the growing summer months (Askew, 2010). Trifloxysulfuron, foramsulfuron, and rimsulfuron are the most commonly used herbicides applied to remove these overseeding grasses in the spring months. Alternatively, these herbicides are also applied prior to overseeding in the autumn for the purpose of controlling weeds, specifically *Poa annua* prior to overseeding establishment (McElroy et al., 2011). *Poa annua* is a very common weed in overseeded *Lolium perenne* and *Poa trivialis* and there are little to no selective postemergence control options to remove *Poa annua* from these turfgrass species (McElroy et al., 2011). *Poa annua* germinates from late summer to early autumn. These herbicides are applied to remove any *Poa annua* that may have germinated prior to overseeding thus reducing Poa annua infestation in the spring. For further information, the authors recommend a review of sulfonylurea herbicides in turfgrass written by Bhowmik (2012).

ACCase inhibiting herbicides

ACCase herbicides inhibiting the enzymatic activity of acetyl-CoA carboxylase a key enzyme in the formation of fatty acids, or lipids (Senseman, 2007). ACCase inhibiting prevents the formation of cellular membranes leading to death of rapidly dividing meristematic tissue.

Herbicides that inhibiting the ACCase enzyme are commonly referred to as graminicides, as they are primarily active on grasses within the Poaceae (formerly, Graminaceae family) (Senseman, 2007). Herbicides that control on grass plants would seemingly have little use in turfgrass. However, ACCase-inhibiting herbicides have developed their niche use on cool-season turfgrass, zoysiagrass, and centipedegrass (Johnson, 1987). There are two ACCase-inhibiting herbicide families that are used in turfgrass: cyclohexanediones and aryloxyphenoxy propionates (Senseman, 2007). Cyclohexanediones are the least utilized in turfgrass because they have the least selectivity. Cyclohexandiones used in turfgrass include clethodim and sethoxydim. Clethodim has little to no selectivity in turfgrass and is used for only non-selective control of both turfgrasses and weeds. Clethodim can be used for bermudagrass control in centipedegrass, but injury to centipedegrass can occur (Waltz et al., 2001; Webster et al., 2004). Sethoxydim is safe on centipedegrass and fine fescue (*Festuca tenuifolia*) for control of bermudagrass, *Digitaria* spp, and *Eleusine indica* (Johnson, 1987). Differential sensitivity between tolerant turfgrass and intolerant turfgrass or weeds is due to differences in metabolism as tolerant species rapidly metabolize sethoxydim in tolerant species (McCarty et al., 1990). Both clethodim and sethoxydim effectively control torpedograss (Panicum repens) in centipedegrass (Taverner et al., 2011). Recent research has focused on developing herbicide resistant seashore paspalum (*Paspalum vaginatum*) using a common single base pair mutation found in weed species (Heckart, 2010). Genetically-modified seashore paspalum will greatly improve weed control options for this species which has few herbicide options.

Aryloxyphenoxy propionate (AOPP) herbicides are more commonly used in turfgrass compared to cycylohexanediones due to greater turfgrass tolerance. There are three AOPP herbicides used in turfgrass: diclofop, fenoxaprop, and fluazifop. Diclofop has a very limited, albeit important, turfgrass use. Diclofop is registered for goosegrass control in bermudagrass golf course turfgrass. Normally such a limited use would preclude the registration of a herbicide; however, diclofop was registered due to the lack of other products to control goosegrass in bermudagrass (McCarty, 1991). Multiple applications of diclofop are needed and goosegrass control can vary with mowing height (McCarty, 1991). Fenoxprop has broader use with potential use on cool-season turfgrass and zoysiagrass. Fenoxaprop controls *Digitaria* spp. at various growth stages, but control can decrease at high volume applications using flood-type nozzles (Neal et al., 1990). Fenoxaprop can be safely used for weed control during seeded establishment of perennial ryegrass and tall fescue with no loss in stand reduction (Dernoeden, 1987). Fenoxprop is also effective for bermudagrass suppression in cool-season turfgrass; however multiple applications are needed for complete control (Johnson & Carrow, 1995). Fluazifop is used in a similar fashion as fenoxaprop. It can be used for bermudagrass and various warm-season annual grass control (Teuton et al., 2005). Fluazifop can be applied to Kentucky bluegrass (*Poa pratensis*) as long as minor injury can be tolerated (Teuton et al., 2008)

A very unique use of both fluazifop and fenoxaprop is the combination of these herbicides with triclopyr for bermudagrass control in zoysiagrass turf (McElroy & Breeden, 2006). Triclopyr plus fluazifop or fenoxaprop not only increases bermudagrass control but it decreases the potential injury zoysiagrass; thus synergizing activity on one species and simultaneously antagonizing on another species. These combinations can be applied at various rates and timings in order to optimize control and improve zoysiagrass turf quality (Lewis et al, 2010). Triclopyr can also be applied with AOPP herbicides not labeled for turfgrass use- metamifop, clodinafop, and quizalofop- and achieve similar effectiveness (Doroh et al, 2011a). Curiously, the synergism/ antagonism effect achieved by triclopyr cannot be duplicated with fluroxypyr; thus it seems that this unique effect is a aberration of a single chemical and does not equate to the entire pyridine family (McElroy & Breeden, 2006).

Non-selective herbicides

Non-selective postemergence herbicide typically used in turfgrass include glyphosate, glufosinate, diquat, and paraquat. Glyphosate is a systemically translocated non-selective postemergence herbicide in the glycine family that inhibits 5-enolpyruvate shikimate-3-phosphate synthase (Senseman, 2007). Glufosinate is a contact non-selective herbicide in the glycine family that inhibits glutamine synthetase (Senseman, 2007). Although similar chemical, glyphosate and glufosinate act very different biochemically thus resulting in different plant responses. Diquat and paraquat are contact non-selective postemergence herbicides in the bipyridilium family that are diverters of electrons from photosystem I (Senseman, 2007). Glufosinate, paraquat, and diquat are three of the fastest acting postemergence herbicides used today causing symptoms in <3 hours under optimum conditions.

Non-selective herbicide can be used for turfgrass renovation and for weed control during warm-season turfgrass dormancy (Johnson, 1998; Doroh et al., 2011b). Use during turfgrass dormancy is limited to areas where warm-season turfgrasses enter complete dormancy during winter months (Johnson & Ware, 1978). "Complete dormancy" often complicates the application non-selective herbicides, as it is difficult to determine when turfgrass enters dormancy. Unseasonably warm winter months can often negate the use of non-selective herbicides. Further, warm-season turfgrasses differ in the dormancy level in which they enter. For these reason, non-selective herbicide are primarily only used on bermudagrass during dormant winter months as other warm-season turfgrass are less adaptable to such application scenarios.

Glyphosate is the primary herbicide use for dormant winter weed control in bermudagrass turf (Johnson & Ware, 1978). Glyphosate applications to dormant bermudagrass were first reported in 1976 (Johnson, 1976). Glyphosate applied at 0.6 kg ha^{-1} controlled winter annual weeds such *Alchemilla microcarpa*, *Veronica arvensis*, *Lamium amplexicaule*, *Poa annua*, and *Stellaria media* with no damaging effects to the bermudagrass. More recent research has confirmed the effectiveness of glyphosate for winter weed control but report that early winter applications are less effective than late winter glyphosate applications presumably due to the lack of residual control (Toler et al., 2007). Researchers also reported that similar weed control during turfgrass dormancy could be achieved with flazasulfuron, foramsulfuron, rimsulfuron, and trifloxysulfuron which pose much less chance of injury due to safety to actively growing bermudagrass (Toler et al., 2007). However, while semi-dormant bermudagrass can be injured by glyphosate it has been reported that turfgrass recovers by the summer months (Johnson and Ware, 1978; Johnson, 1980a).

Glufosinate, diquat, and paraquat are considered less effective than glyphosate for dormant weed control due to their limited translocation potential. Glufosinate has been reported to effectively control *Poa annua*; however, mixtures of glufosinate with clethodim or glyphosate are considered consistently more effective (Toler et al., 2007). Paraquat effectively control *Veronica arvensis* and *Lamium amplexicaule* more consistenly than 2,4-D alone (Johnson, 1975a). But in the opinion of the author, these are only two species and neither paraquat nor diquat are known for their broad-spectrum control especially of larger plants.

FINAL THOUGHTS

Turfgrass weed control requires the use of numerous modes of action to control the diversity of weeds that can be present. Herbicides are developed initially for the large agricultural food and fiber production market and use in turfgrass is often an after thought. Considering that turfgrass is a perennial crop, herbicide use can often change drastically when moved from agriculture to turfgrass (e.g., sulfentrazone is a preemergence herbicide in crops and postemergence herbicide in turfgrass). Niche areas often develop when testing herbicides for turfgrass use and such uses are often not the research target (e.g., carfentrazone control silver-thread moss which was discovered by accident).

While herbicide resistant weeds were not discussed, development of weed resistance to herbicides will be a major obstacle to herbicide use in turfgrass. The International Survey of Herbicide Resistance (http://www.weedscience.com) currently reports *Poa annua* resistance to photosystem

II inhibitors (atrazine, simazine, diuron), photosystem I inhibitors (paraquat), inhibitors of very long-chain fatty acids (ethofumesate), mitotic-inhibiting herbicides (prodiamine, pendimethalin) and 5-enolpyruvate shikimate-3-phosphate inhibitors (glyphosate). Resistance has been reported for *Eleusine indica*, *Digitaria* spp., *Lolium perenne, Lolium multiflorum*, and *Stellaria media* as well. The combination of herbicide loss by unnecessary environmental regulation and increased herbicide resistance will be a challenge for turfgrass weed control in the future.

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