Use of 2,4-D and Other Phenoxy Herbicides in Turfgrass in the United States

Kai Umeda, University of Arizona

- The use of 2,4-D on turfgrass was one of the first uses of the selective herbicide.
- 2,4-D is the most commonly used herbicide for turfgrass weed control in the combined industrial/commercial/governmental sector, with applications in 2007 totalling between 19 and 22 million pounds.
- Applications of 2,4-D in the home and garden sectors totalled between 8 and 11 million pounds.
- 2,4-D remains a critical tool for controlling broadleaf weeds in turfgrass.

Introduction

Turfgrass covers 40 million acres in the United States (US) on residential lawns, parks and school playgrounds, golf courses and sports fields, commercial and institutional landscapes and cemeteries. Broadleaf weeds can occur in all turfgrass areas whether intensely manicured or less maintained with infrequent care. Many weeds in turfgrass are controlled by integrated management practices that prevent weeds, such as proper mowing, fertilizing, irrigating and hand pulling. However, when broadleaf and grass weed populations overrun a turf site, herbicides can be used to reduce the infestation. Common broadleaf weeds in turfgrass include dandelions, dead nettle, and plantains. Among the most commonly used herbicides against broadleaf weeds are synthetic auxins and phenoxy herbicides such as 2,4-D, MCPA, mecoprop, and dichlorprop. Other herbicide chemistries are often used in combination with 2,4-D or phenoxy herbicides to reduce application rates and increase the spectrum of broadleaf weed control. In 2007, the amount of all herbicide active ingredients used in the US for the industrial, commercial, and governmental sectors, as well as home and garden, was 89 million pounds. Of that, an estimated 33 million pounds was 2,4-D.

Since the 1990's, ALS-inhibiting and PPO-inhibiting herbicides have been expanding the options for turf managers to select herbicide products that specifically target problem weeds. These herbicides could be further investigated, and labels could be expanded to include more broadleaf weeds. There are also turfgrasses being bred to tolerate non-selective herbicides, a promising avenue of research. These technological advances could assure reliable broadleaf weed control in turfgrasses. Continued availability of the phenoxy herbicides – together with the ALS-inhibiting and PPO-inhibiting herbicides – as well as the older triazines will prevent weeds from developing resistances by using effective herbicide rotations.

Retaining 2,4-D and the phenoxy herbicides for broadleaf weed control is critical to ensure that applicators will have a wide array of choices for managing quality turf. Eliminating 2,4-D or an entire class of herbicides will severely limit the alternatives that are available to a broad range of end-users, from professional golf course superintendents and sports turf managers to landscapers and homeowners.

Turfgrasses

The turfgrass industry in the US is divided into five sectors and generated $62.2 billion of total output impacts, $37.7 billion in value added, $24.7 billion in labor income, and paid $2.6 billion in indirect business taxes and generated 822,849 jobs (Haydu et al. 2006). The turf industry's value in 1992 was $20-30 billion (Watson et al. 1992).

Eliminating 2,4-D or an entire class of herbicides will severely limit the alternatives that are available to a broad range of end-users from professional golf course superintendents and sports turf managers to landscapers and homeowners

In the US, there are 98,817 K-12 public schools in 13,588 public school districts, and 33,366 private schools (Keaton 2014, USED 2012a). There are 4,599 two- and four-year colleges plus an additional 2,422 other postsecondary institutions (USED 2012b). Most higher education institutions have athletic facilities for sports teams that have fields managed by sports turf managers (Umeda and Fournier 2012). Additionally, professional sports turf managers maintain turfgrasses in professional sports stadiums across the US.

Turfgrass covers over 40 million acres in the US (Milesi et al. 2005). The US can be divided into a cool-season grass growing zone and a warm-season grass zone. In between the cooler, temperate zone and the warmer tropical/arid zone, there is a transition zone where both types of grasses can be grown, from the Carolinas through Kentucky, Arkansas, Oklahoma, and into the southwest. Cool-season turfgrasses are comprised of bluegrasses, ryegrasses, fescues, and bentgrasses. The warm- season turfgrasses are comprised of Bermudagrasses, zoysiagrass, bahiagrass, centipedegrass, St. Augustinegrass, buffalograss, and seashore paspalum. There are other grasses, but they are generally less common in turf.

High intensity management practices and strategies are required for professional sports stadium turfgrasses. They are also highly desirable for private and resort golf courses for optimal performance and playability. Streetscapes, municipal parks, cemeteries, and institutional grounds generally maintain turf for aesthetic and general purpose uses, requiring less intense management practices.

The expectations for varying levels of desirable turfgrass quality are subjective among professional golf course superintendents, sports turf managers, commercial lawn care operators, and homeowners. The desired aesthetic appearance, color, density, uniformity, and smoothness of a turf can be varied and levels of tolerance for weeds, pests, and diseases depend on personal or desirable preferences.

Properly managed, turfgrass can be very competitive against the invasion of weeds. Management practices – such as proper mowing, fertilization, aeration, and others – can promote a healthy and vigorously growing turf to limit and/or reduce weed seedling establishment. The best deterrent to weeds is a dense and vigorously growing turf that is adapted to the site. Most annual weeds have difficulty becoming established when intense management practices are imposed upon a turf. However, some perennial weeds, once established, usually require a herbicide treatment for effective control.

Benefits

Well maintained turf – in parks, on lawns, or other community spaces – has a number of secondary benefits beyond its aesthetic appeal. In urban spaces, properly maintained lawns and park greenery have distinct advantages over bare pavement. Turfgrasses help regulate air quality and temperature, where a small lawn of 2500 sqft will remove roughly 25 lbs of carbon dioxide from the atmosphere annually (Zirkle et al 2011). Surface temperatures increased dramatically over 50F on asphalt compared to grass (Bulut et al 2008). This in turn helps lower greenhouse gas emissions, as the temperature regulating effects of turf reduce the need for air conditioning : eight healthy front lawns have the cooling effect of 70 tons of air conditioning (McPherson et al, 1989). One estimate suggests that strategic planting of lawns and other landscape plants could reduce a household's annual energy requirements by 25 percent (US Department of Energy, 2014). Keeping those lawns healthy is a task to which 2,4-D is well suited, eliminating broadleaf weed competition but leaving the desired grass untouched

Turf acts as a natural filter for rainwater, reducing runoff of sediment, fertilizer, and other substances best kept out of groundwater. This effect is further amplified by turf's ability to reduce soil erosion, further reducing the amount of undesirable materials flowing into lakes and rivers.

The substantial root networks of grasses make turf an ideal plant to stabilize soils, reducing dust in dry conditions and runoff in wet conditions.

There is an ever growing amount of research indicating positive societal and community benefits brought about by green spaces with turf. Such benefits include improved health, reduced crime, and improved mental health. More concretely, turf has significant economic impacts in a number of areas. Well maintained landscaping has been found to increase property values in a number of different studies (Des Rosiers, 2003). Lawncare alone has created over 500,000 jobs in the US (Maryland, 1996), and generated billions in economic growth in multiple states (Duval et al, 2016). Golf courses are a prime example of the economic benefits of turfgrasses, driving tourism, construction, and improving housing prices. The total economic impact of golf in the US is estimated to be in the vicinity of $176 billion. Golf also directly or indirectly provides some 2 million jobs across the country. 2,4-D is an integral tool for keeping golf courses operational at acceptable costs.

Weed Occurrences in Turfgrasses

Weeds can be categorized several ways; the most common is as either broadleaf dicots or grassy monocots. Another categorization is by life cycle; annual plants that grow in a single season, biennial plants that grow over two years, and perennial plants that grow back every year. Lastly, they can be categorized as warm-season and cool-season plants, much like the grasses they compete with.

Weeds occur in turf seasonally Summer annual weeds generally begin to appear in the spring and persist throughout the summer months. Winter annual weeds germinate in cooler temperatures during the fall, winter, and spring seasons. Both summer and winter annual weeds include broadleaf species and grasses. Perennial weeds – both broadleaf and grassy – appear in the spring and throughout the summer and are dormant during the cold winters. Both broadleaf and grass weeds can germinate, emerge, establish, and mature when the temperatures are conducive for their growth. They are highly adaptable to the environmental conditions; for example, lower mowing heights can force a typically tall weed to grow horizontally. However, weeds generally require exposed soil and suitable moisture levels to infest turf. Planting time can provide such an opportunity; there is plenty of exposed soil, and the water used to help the grass grow is equally helpful to the weeds. Later in turf lifetime, disturbances from use can expose soil, while irrigation or rainfall can provide the necessary moisture.

Common Weed Problems and Their Control

Several broadleaf weed species can be found in turfgrass (Turgeon 1991; Vaughn et al. 1990). Annual species commonly occur in turfgrass, but many are controlled by mowing. Perennial species are not controlled effectively by mowing, so they generally require treating with an herbicide. Dandelion, broadleaf plantain, buckhorn plantain, field bindweed, speedwells, clovers, curly dock, and creeping woodsorrel are a few of the many perennial species infesting turfgrass.

A 1992 survey indicated that dandelion was reported by 73% of the respondents to be either the most important or next to most important weed in turfgrass (Elmore 1996). Broadleaf plantain and buckhorn plantain were also listed as the top 3 or 4 weeds of concern in many states.

Weed susceptibility to various herbicides varies considerably. No one herbicide controls all weed species in turfgrass and is still selective to turf. Most phenoxy herbicides can be used selectively in turfgrasses while many broadleaf weeds have levels of relative susceptibility (Table 5.1). Many annual weed species may be controlled with preemergence herbicides; however, annual weeds that become established or perennial weeds require post emergence herbicides such as 2,4-D for effective control.

Table 5.1. Broadleaf weeds in turf with relative susceptibility to phenoxy herbicides.

aster	dandelion	lupine	ragwort, tansy
beggarticks	dock	mallow	rape, wild
bindweed	dogbane	marshelder	rocket, yellow
bittercress	evening primrose	morning glories	salsify
bitterweed	flixweed	mousetail	shepherdspurse
blue lettuce	galinsoga	mustards	sicklepod
blueweed, Texas	garlic, wild	nettles	smartweed
broomweed	geranium, Carolina	onion, wild	sneezeweed
bullnettle	goldenrod	parsnip, wild	sowthistles
burdock	hawkweed	pennycress	Spanish needles
buttercup	healall	pennywort	sunflower
carpetweed	hemp, wild	pepperweeds	sweetclover
carrot, wild	horseweed (marestail)	pigweeds	tansymustard
catnip	ironweed	plantains	thistle, bull
chicory	ivy, ground	poorjoe	thistle, Canada
cinquefoil	jewelweed	primrose	thistle, musk
cocklebur	jimsonweed	purslane	thistle, Russian
coffeweed	knotweed	pusley, Florida	velvetleaf
copperleaf	kochia	radish, wild	vervains
cress, hoary	lambsquarters	ragweed, common	vetches
croton	lettuce, prickly	ragweed, giant	wormwood

Turfgrass species vary in their susceptibility to herbicides (Vaughan 1990). Most cool-season turfgrasses are tolerant of the synthetic auxin herbicides. Tall fescue, perennial ryegrass, and Kentucky bluegrass are the most tolerant to these herbicides. Bentgrass that is frequently used on golf coarse greens will tolerate mecoprop or dicamba, but only very low rates of 2,4-D (Patton et al. 2013). The warm-season turfgrass species, Bermudagrass, bahiagrass and St. Augustinegrass, are not tolerant of the synthetic auxin herbicides, especially at summertime temperatures exceeding 90°F.

Most weeds in turfgrass can be controlled selectively with herbicides. It is important to select the appropriate herbicide for the target weed, as well as to apply the appropriate amount of herbicide at the correct stage of the weed's growth. Weed control is achieved when the plants are completely desiccated and necrotic or when their growth ceases becoming competitive with turf. 2,4-D treated weeds exhibit twisted and distorted foliage and stems, followed by necrosis of the plant. Although eradication of weeds is not always possible, control is usually adequate for the turfgrass to crowd out most remaining weeds.

Turfgrass weed control is practiced by professional golf course superintendents, sports turf managers, commercial lawncare operators, and homeowners. In residential and commercial landscapes, there would be a loss in value of the property if broadleaf weeds were prevalent in the lawn. Landscape quality directly affects residential sales prices. Prices increased 8.9 to 10.4% for homes with good landscaping compared to poor or average landscaping. Excellent landscaping increased home values an additional 4.0 to 4.6% (Henry 1994). Homeowners spent nearly $45 billion for professional lawn and landscape services in 2006 (Butterfield 2007). Lawncare and landscape maintenance services were hired by 27.8 million households in the same year (Butterfield 2007).

Landscape quality directly affects residential sales prices. Prices increased 8.9 to 10.4% for homes with good landscaping compared to poor or average landscaping. Excellent landscaping increased home values another 4.0 to 4.6% over good landscaped homes (Henry 1994).

Current Herbicide Control Methods

Broadleaf weeds are physiologically different from turfgrasses and grass weeds. Broadleaf weeds appear obviously out of place when they disrupt the uniformity and smoothness of the turf surface, or interfere with sunlight by shading the turf. Since broadleaf weeds are the more unsightly variety, there is a strong desire to control these weeds. Selective control of broadleaf weeds can be achieved by using the phenoxy and other classes of herbicides, either individually or more commonly in combinations.

Selective broadleaf weed control can be achieved in turfs when various classes of postemergence herbicides are integrated in a management strategy (Table 5.2). Postemergence herbicides can be used individually or in combinations. A combination of post emergence herbicides can be applied by tank-mixing two or more products, or the manufacturer can formulate multiple active ingredients in a pre-mix product.

Table 5.2. Herbicide efficacy against common broadleaf weeds in turfgrasses (Guillebeau and Pettis 2004). E=Excellent, G=Good, F=Fair, P=Poor

	atrazine	bentazon	bromoxynil	carfentrazone	clopyralid	2,4-D	2,4-D + 2,4-DP	2,4-D + dicamba	2,4-D + triclopyr	dicamb	dicoofop	fenoxapro	fluroxypr
chamberbitter	G	P			P	P					P	P	
chickweed, common	E	G	P	G	P	P	G	G	E	E	P	P	G
chickweed, mouseear	G	P			P	P-F	G	G	G	E	P	P	G
corn speedwell	E	P	G	G		F	F	F	G	F	P	P	
cudweed	G		G		E	G-E	G-E	E	G-E	E	P	P	
dandelion	F	P	P	G	F	E	G	G	G	E	P	P	F-G
dichondra	F	P	P			G	G	G		G	P	P	
docks	G	P			G	F	F	G	F-G	E	P	P	
doveweed	G-E	P	P		P	P	F	F	F	P	P	P	
Florida betony	F-G	P	P		P	F	G	G	G	G	P	P	
ground ivy		P	P	G		P-F	F	F	G	G	P	P	G
henbit	E	P	G	G		P	G	G	E	E	P	P	F-G
hop clovers	E		F		E	F	E	G	E	E	P	P	
knotweed	E		F			P	F	G	F	E	P	P	G
lespedeza	E				P	P-F	G	G		E	P	P	
mallow, bristly		P				F	F-G	F-G	G	E	P	P	
mock strawberry		P				P	P	G		G	P	P	
mugwort		P				F	F	F		G	P	P	
mustards	E	G	G		P	E	G	G		E	P	P	
parsley piert	E	G	G		P	P	P		E	E	P	P	
pennywort	E	P	P			G	G	G		E	P	P	
plantains	F	P	P			E	G	G	G	F	P	P	F-G
spurges	E	P	F	E		F	G	G	G	G	P	P	
spurweed (burweed)	E	E	G		E	G	E	G	E	E	P	P	
star-of-Bethlehem	P	P	G		P	P	P	P	P	P	P	P	
Virginia buttonweed		P	P			P	F	F	F	F	P	P	F
violets		P				P	F	F	F	F	P	P	
white clover	E	P			E	F	G	G	G	E	P	P	E
woodsorrel	G	P	F			P	P-F	F	F	G	P	P	G

Selective postemergence herbicides include 2,4-D and the other phenoxy herbicides. There are four phenoxy herbicides available for use in turf including 2,4-D, mecoprop (MCPP), MCPA, and dichlorprop (2,4-DP). The phenoxy herbicides are effectively used against most broadleaf weeds in most turfgrasses. Not all of the phenoxy herbicides are equally effective against broadleaf weeds.

Sales and Use of Herbicides

Estimates of total pesticide expenditures in the US in 2007 for the home and garden and industrial/commercial/governmental sectors were nearly $4.6 billion. This represented 36% of total herbicide sales in 2007, while agricultural uses accounted for the other 64%(Grube et al. 2011). The industrial/commercial/governmental sector accounts for all sales to licensed professionals for commercial applications, including home gardens and lawns. That sector, along with non-professional home and garden applicators, used 89 million pounds of herbicides in 2007. In comparison, all other pesticides (miticides, fungicides, nematicides, fumigants etc.) saw use in the vicinity of 84 million pounds. The pesticide active ingredient most commonly used in the home and garden market sector was 2,4-D, at between 8 and 11 million pounds (Grube et al. 2011). This estimated use for 2007 was the same as in 2001. For the industrial/commercial/governmental sector, 2,4-D ranked number 1 in 2007, with uses ranging from 19 to 22 million pounds. In 2001, it ranked number 1 as well, and 16 to 18 million pounds were used.

The pesticide active ingredient most commonly used in the home and garden market sector was 2,4-D at between 8 and 11 million pounds (Grube et al. 2011).

Other commonly used herbicides in the home and garden market sector were; glyphosate, which was ranked number 2 (5 to 8 million pounds), MCPP at number 4 (4 to 6 million pounds), dicamba at number 8 (1 to 3 million pounds), and pelargonic acid ranked number 10 (< 1 million pounds) (Grube et al. 2011). The above herbicides are all post emergence products, with 2,4-D, MCPP, and dicamba being commonly used selectively in turf against broadleaf weeds. Preemergence herbicides such as pendimethalin and trifluralin were ranked number 5 (3 to 5 million pounds) and number 9 (1 to 3 million pounds), respectively. In 1984, it was estimated that $1.2 billion worth of pesticides were sold to the turfgrass industry, of which $716 million were post emergence herbicides (Watschke et al. 1994). Then, as today, the phenoxy herbicides and dicamba were the predominate post emergence herbicides.

Synthetic auxins

Auxins are naturally occurring plant hormones. The auxin-mimicking herbicides cause abnormal stimulation of cell division and uncontrolled plant growth. The synthetic auxin herbicides used for turf include 2,4-D, mecoprop, MCPA, dichlorprop, MCPB, dicamba, triclopyr, clopyralid, and fluroxypyr.

Most of the synthetic auxin herbicides (2,4-D, mecoprop, MCPA, dichlorprop, MCPB, and dicamba) are typically formulated in pre-mix combination products. Most often, a three-way mixture of 2,4-D, mecoprop, and dicamba is applied. The strengths of each individual herbicide are combined to offer a broader spectrum of broadleaf weed control.

Weed Resistance Management with Phenoxy Herbicides

There are currently 437 unique cases of herbicide resistant weeds globally, with 238 species (138 dicots and 100 monocots) (Heap 2014). Weeds have evolved resistance to 22 of the 25 known herbicide sites of action and to 155 different herbicides. Broadleaf weeds that can occur in turf have developed resistance to 2,4-D (Heap 2014). Goosegrass (USED 2012b) and green foxtail (Westra 1993) have shown resistance to the dinitroanilines, a family of preemergence herbicides used in turf. There have also been reports that smooth crabgrass is tolerant to quinclorac, a herbicide used in turfgrass. A number of weeds such as goosegrass, crabgrasses, and Poa annua have been found to be resistant to dinitroanilines, photosystem II- inhibiting herbicides, acetylCoA carboxaylase-inhibiting herbicides, as well as ALS-inhibiting herbicides.

Since the late 1980's, no new herbicidal mechanisms of action have been introduced into the agricultural or turfgrass marketplaces (Duke 2012). Continued availability of the phenoxy herbicides together with a spectrum of multiple modes of action will ensure that effective herbicide rotations could be implemented to manage and minimize the evolution of weed resistance to herbicides in turf.

Future Weed Management Options

Turfgrass management requires various levels of inputs to obtain a particular degree of desired turf quality. All managed turfgrasses are mowed, irrigated, and fertilized to some degree. Highly manicured and intensely managed golf courses, sports fields, and residential landscapes are typically mowed frequently. Additionally, fertility and irrigation are monitored and scrutinized to promote dense turf which reduces weed intrusion. Lesser maintained lawns, playgrounds, and streetscapes are mowed less frequently, fertilized less (if ever), and minimally irrigated aside from rainfall. Turfs in these situations are more susceptible to weed invasions and infestations. Improving turf quality by mowing, fertilizing and irrigating can enhance the aesthetics and safe function of a turf.

For both situations, weed control can be supplemented by the use of preemergence and selective post emergence herbicides. Specifically, post emergence herbicides can be applied for broadleaf weed control – either with or without 2,4-D – in combined pre- mix products. Other synthetic auxins such as mecoprop, MCPA, dichlorprop, MCPB, dicamba, triclopyr, clopyralid, and fluroxypyr can be used alone or in combinations to provide effective broadleaf weed control.

Combination pre-mix products include the synthetic auxins together with the PPO-inhibiting herbicides carfentrazone or sulfentrazone. These combinations widen the spectrum of weeds controlled, enhance visual herbicide activity, and can improve efficacy of applications made during suboptimal temperatures.

The ALS-inhibiting herbicides – including metsulfuron, rimsulfuron, trifloxysulfuron, and flazasulfuron – are effective herbicides for broadleaf weed control in warm-season turf (Table 5.2). Combination pre-mix products, which contain ALS-inhibitors and synthetic auxins like Dicamba, have been introduced for broad-spectrum weed control in turfgrasses.

Following initial introductions in major crops such as corn, wheat, or rice, Herbicide manufacturers are continuously investigating active ingredients for turfgrass use. Formulators are exploring combinations of herbicides that expand the spectrum of weeds controlled, or that will target hard-to-control weeds. As older herbicides continue to be used effectively and safely, innovative formulations and combinations are being developed to extend the patent life of products.

In the future, turfgrass breeding efforts will lead to introduction and marketing of herbicide tolerant turfgrasses. There already exist bentgrass cultivars that are tolerant to glyphosate; however, these cultivars are not commercially available (USDA 2003). Other cool- season grasses like Kentucky bluegrass are being genetically modified to tolerate broad spectrum, nonselective herbicide treatment, and likely will become commercially available in coming years. Perennial ryegrass cultivars have been found to be tolerant of glyphosate through traditional breeding methods, and are currently commercially available. Though it may be exceedingly expensive, hand weeding may be necessary on some intensely managed turfgrass areas for control of perennial broadleaf weeds.

The phenoxy herbicides including 2,4-D, mecoprop, MCPA, dichlorprop, MCPB are major components for effective broadleaf weed control programs in turfgrass.

Conclusions

The phenoxy herbicides – including 2,4-D, mecoprop, MCPA, dichlorprop, and MCPB – are major components for effective broadleaf control programs in turfgrass. The phenoxy herbicides are typically formulated and sold as combination pre-mix products. Other synthetic auxins such as dicamba, triclopyr, clopyralid, and fluroxypyr are also combined with the phenoxy herbicides to enhance efficacy against a wider range of broadleaf weeds.

The safety of 2,4-D has been improved by formulators with longer chain ester formulations that are less prone to off-target drift. Formulations such as spreadable granules integrated with fertilizers enable improved applications to turfgrass weeds.

Introductions and explorations of ALS-inhibiting and PPO-inhibiting herbicides are expanding options for turf managers. It is probable that more recently introduced herbicides such as penoxsulam, flazasulfuron, and sulfosulfuron could be further investigated, and that labels could be expanded to include more broadleaf weeds.

2,4-D and the phenoxy herbicides for broadleaf weed control in turfgrasses is critical to ensure that turf managers will have a wide array of choices for managing quality turf and managing the evolution of herbicide resistant weeds.

Retaining 2,4-D and the phenoxy herbicides for broadleaf weed control is critical to ensure that turf managers have a wide array of choices for maintaining quality turf and preventing the evolution of herbicide resistant weeds. Eliminating 2,4-D or an entire class of herbicides would severely limit the alternatives that are available to a broad range of end-users, from professional golf course superintendents and sports turf managers to landscapers and homeowners.

Additionally, loss of access to 2,4-D would increase the risk of weeds developing resistance to other chemistries by limiting options available to turfgrass managers for selective post emergence control.

ACKNOWLEDGMENT

I thank Jim Brosnan and Gary Custis for their valuable insights and inputs for this chapter.

LITERATURE CITED

BULUT, Y & Toy, Süleyman & Irmak, Mehmet & Yilmaz, Hasan & Yilmaz, Sevgi. (2008). Urban-rural climatic differences over a 2-year period in the City of Erzurum, Turkey. Atmósfera. 21. 121-133.

Butterfield, B. 2007. Market research. The National Gardening Association. Williston, VT. URL: http://www.gardenresearch.com/index.php?q=show&id=2872 Retrieved December 2014.

Des Rosiers, Francois, et al. 2003. Landscaping and House Values: An Empirical Investigation, Laval University, and Smart Money Magazine

Diep, F. 2011. URL: http://scienceline.org/2011/07/lawns-vs-crops-in-the-continental-u-s/ Retrieved December 2014.

Duke, S.O. 2012. Why have no new herbicide modes of action appeared in recent years? Pest. Madag. Sci. 68: 505–512. doi: 10.1002/ps.2333.

Duval, D., Kerna, A., Frisvold, G., Umeda, K., & Li, R. (2016). Contribution of the Golf Industry to the Arizona Economy in 2014. Tucson: University of Arizona.

Elmore, C.L. 1996. In: Biologic and economic assessment of benefits from use of phenoxy herbicides in the United States [National Agricultural Pesticide Impact Assessment Program, NAPIAP Report Number 1-PA-96; November 1996]. US Department of Agriculture, National Agricultural Pesticide Impact Assessment Program (NAPIAP), Washington, D.C.; 242 pp.

Guillebeau, P. and G.V. Pettis. 2004. Pest Management Strategic Plan for Turfgrass in the Southern United States. October 2004. Southern Region Integrated Pest Management Center, US Department of Agriculture, Cooperative State Research, Education, and Extension Service, and USDA Office of Pest Management Policy. University of Georgia, Griffin, GA. URL: www.ipmcenters.org/pmsp/pdf/southernturfgrass.pdf Retrieved December 2014.

Grube, A., D. Donaldson, T. Kiely, and L. Wu. 2011. Pesticides industry sales and usage, 2006 and 2007 market estimates. Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, US Environmental Protection Agency. Washington, DC 20460. February 2011. URL: http://www.epa.gov/opp00001/pestsales/07pestsales/market_estimates2007.pdf Retrieved December 2014.

Haydu, J.J., A.W. Hodges, and C.R. Hall. 2006. Economic impacts of the turfgrass and lawncare industry in the United States. University of Florida, Institute of Food and Agricultural Sciences, Food and Resource Economics Department, EDIS number FE632, April 2006. Gainesville, FL. URL: edis.ifas.ufl.edu/pdffiles/FE/FE63200.pdf Retrieved December 2014.

Heap, I. 2014. International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx Retrieved December 2014.

Henry, M.S. 1994. The contribution of landscaping to the price of single family houses: A study of home sales in Greenville, South Carolina. J. Environ. Hort. 12:65-70.

Keaton, P. 2014. Selected statistics from the public elementary and secondary education universe: school year 2012–13 (NCES 2014-098). US Department of Education. Washington, DC: National Center for Education Statistics. URL: http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=201498 Retrieved December 2014.

McPherson, Gregory E., Simpson, James R., Livingston, Margaret. 1989. Effects of three landscape tratments on. Residential energy and water use in Tucson, Arizona Energy and Buildings, 13 127-38

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. Manag. 36 (3):426-438.

Morris, K. 2003. The National Turfgrass Research Initiative; April 2003. National Turfgrass Federation, Inc. National Turfgrass Evaluation Program, Beltsville Agricultural Research Center-West, Beltsville, MD. 22 pp. URL: www.ntep.org/pdf/turfinitiative.pdf Retrieved December 2014.

Patton, A.J., D.V. Weisenberger, J.T. Brosnan, and G.K. Breeden. 2013. Creeping bentgrass putting green tolerance to postemergence herbicides for broadleaf weed control. Applied Turfgrass Science. doi:10.1094/ATS-2013-0523-01-BR.

Shaner, D.L. ed. 2014. Herbicide Handbook 10th edition. Champaign, IL: Weed Science Society of America.

Stier, J.C., B.P. Horgan, S.A. Bonos, eds. 2013. Turfgrass: Biology, Use, and Management. Agron. Monograph 56, Am. Soc. Agron., Madison, WI.

Turgeon, A.J. 1991. Turfgrass Management. Prentice Hall, Englewood, NJ. 418 p.

Umeda, K. and A. Fournier. 2012. Pest Management Strategic Plan for Turfgrass in the Low Desert Regions of Arizona, Southern California, and Southern Nevada-Southern Utah. June 2012. Western Region Integrated Pest Management Center, US Department of Agriculture, Cooperative

State Research, Education, and Extension Service, and USDA Office of Pest Management Policy. University of Arizona, Phoenix, AZ. URL: www.ipmcenters.org/pmsp/pdf/AZ-CA-NV-UTdesertturfgrassPMSP.pdf Retrieved December 2014.

University of Maryland. 1996 Maryland Turfgrass Survey. An Economic Value Study. Institute of Applied Agriculture. University of Maryland, College Park.

(USDA) US Department of Agriculture. 2003. APHIS Preliminary Risk Assessment on the Petition for a Determination of Nonregulated Status for Creeping Bentgrass (Agrostis stolonifera) Genetically Engineered (Event ASR368) for Tolerance to the Herbicide Glyphosate submitted by Monsanto Company and the Scotts Company. URL: http://www.aphis.usda.gov/brs/aphisdocs/03_10401p_ra.pdf Retrieved February 2015.

(USED) US Department of Education. 2012. Institute of Education Sciences, National Center for Education Statistics. Digest of education statistics. [Internet] URL: http://nces.ed.gov/programs/digest/d12/tables/dt12_098.asp Retrieved December 2014.

US Department of Education. 2012. Institute of Education Sciences, National Center for Education Statistics. [Internet] URL: http://nces.ed.gov/fastfacts/display.asp?id=84
Retrieved December 2014.

US Department of Energy. 2014. Energy Saver: Tips on Saving Money & Energy at Home. p. 18. Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy. http://energy.gov/sites/prod/files/2014/05/f16/Energy_Saver_Guide_PhaseI_Final.pdf. March 2014

Vaughn, K.C., M.A. Vaughan, and B.J. Gossett. 1990. A biotype of goosegrass (Eleusine indica) with an intermediate level of dinitroaniline herbicide resistance. Weed Technol. 4:157-162.

Watschke, T.L., P.H. Dernoedon, and D.J. Shetlar. 1994. Managing Turfgrass Pests. Lewis Publishers, Boca Raton, FL. 361p.

Watson, J.R., H.E. Kaer wer, and D.P. Martin. 1992. The turfgrass industry. p. 29-88. in Turfgrass. D.V. Waddington, R.N. Carrow, and R.C. Shearman, eds. Agron. Monograph 32, Am. Soc. Agron., Madison, WI.

Westra, P. 1993. Species diversity and geographic range of herbicides resistant weeds in the western region of North America. Proc. Western Soc. Weed Sci. 46:121-122.

Zirkle, G., R. Lal, and B. Augustin. 2011. Modeling Carbon Sequestration in Home Lawns. HortScience 46:808–814

Kai Umeda is an Area Extension Agent, Turfgrass Science at University of Arizona. His program focuses on developing and conducting an educational extension program to assist professional turfgrass managers in solving priority problems using research based information and technology. Weed control and pest management are areas of emphasis to ensure the future viability of turfgrasses for landscapes, recreation, and sports in the desert.