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# Achieving sustainable turfgrass management

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# Advances in turfgrass weed management

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## 1 Introduction

A weed can be simply defined as 'a plant growing where it is not wanted' (Harlan and deWet, 1965), which puts the onus on humans to determine which plants are weeds. For example, the dandelion (*Taraxacum officinale* F.H. Wigg.) is the epitome of a plant that can be considered both a weed and a desirable plant, depending on the location, purpose, and person. Brought from Europe to the New World intentionally by settlers as a medicinal herb, dandelions are cultivated for use in salad and to make wine, and they are admired for their beauty. Dandelion art and images are widespread in home décor, marketing, and even tattoos (Sanchez, 2006; Struwe, 2018). Contrast this idea with mass market consumer products for broadleaf weed control that contain the image of yellow dandelion flowers or puffball seedheads to attract the customer (Fig. 1). Clearly, there is a wide spectrum of dandelion appreciation.

Among professional turfgrass managers, there is more consensus about superior and inferior vegetation. Cultivated turfgrass species are superior to weeds and provide many environmental and economic benefits, as reviewed by Brosnan et al. (2020c). Weeds such as clover (*Trifolium* spp.) and crabgrass (*Digitaria* spp.) do not possess the full suite of functional and cultural benefits

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**Figure 1** A common consumer herbicide used to control dandelions in lawns.

provided by cultivated turfgrass species (Brosnan et al., 2014). As such, economical and effective weed control in sustainable turfgrass ecosystems is important to maintain both the functional and cultural benefits of turfgrass.

Rapid advances in turfgrass weed control occurred during the post-World War II era with advancements in selective herbicides. Led by the discovery that 2,4-D could selectively control dandelion and other broadleaf weeds without injury to Kentucky bluegrass (*Poa pratensis* L.), new herbicides were central to weed control innovation for many years (Marth and Mitchell, 1944). Highlighting this, L.W. Kephart of the United States Department of Agriculture (USDA; Washington, DC, USA) remarked of 'an intense preoccupation…with weed-killing chemicals and our seeming neglect of other avenues of approach to scientific weed control' during an address at the 1948 Northeastern Weed Control Conference (Kephart, 1948). The first turfgrass article published in the flagship Weed Science Society of America (https://wssa.net) journal *Weeds* was titled 'A comparison of five chemicals for crabgrass control in turf' (Engel et al., 1953). More recently, weed control research is including nonchemical practices more frequently but remains unbalanced toward chemical control research (Harker and O'Donovan, 2013).

While herbicides are important tools for weed management, weeds have developed resistance to herbicides, registration of new herbicide active ingredients has slowed, and government restriction of pesticide use continues to increase (Brosnan et al., 2020a; Duke, 2012). Economical and effective weed control will increasingly rely on strategies that integrate nonherbicide strategies as foundational elements of weed control programs. This will require practitioners to have more expertise on herbicide mode of action and specific cultural control strategies for each weed to provide the weed-free turfgrass desired by their customers. This chapter summarizes the current knowledge on weed control utilizing biological, physical, cultural, and organic control options as well as a look to the future on potential opportunities and challenges related to sustainable weed management in turfgrass ecosystems.

## *1.1 Herbicide development after 2,4-D*

Prior to the development of synthetic herbicides, inorganic molecules were used. Salts of heavy metals including arsenicals were utilized in various systems in the early- to mid-twentieth century (Zimdahl, 2015); however, they were discontinued due to detrimental environmental and human health effects. The first synthetic organic herbicide was dinoseb and was introduced for selective grass and broadleaf weed control in large-seeded crops in 1932 (King, 1966). The first synthetic herbicide used in turfgrass systems was 2,4-D, a phenoxy herbicide, and was first synthesized in 1941 in the UK before obtaining a U.S. patent by F. D. Jones of American Chemical Paint Company (Philadelphia, PA, USA) in 1945 and was commercialized soon thereafter (King, 1966; Peterson et al., 2016). After 2,4-D was commercialized, other auxin mimic herbicides including additional phenoxy-carboxylic acids, benzoic acids, picolinic acids, and pyridinecarboxylic acids were introduced and continue to be commonly applied in cool- and warm-season turfgrass systems today (Table 1). Photosystem II (PSII)-inhibiting herbicides were developed soon thereafter, and atrazine was commercially available for maize in 1958 and later registered for warm-season turfgrass. According to United States Environmental Protection Agency (US EPA) in 2013, simazine (a PSII-inhibiting triazine) was the third most commonly used preemergence herbicide used in sod production and the second most commonly used preemergence herbicide used on golf courses (approximately, based on the amount of active ingredient applied) (US EPA, 2020). Triazine herbicides remain a very important herbicide family in the USA, although they are regulated and have additional use restrictions recently imposed due to groundwater contamination potential, among other reasons. Protoporphyrinogen oxidase (PPO)-inhibiting herbicides were initially discovered in the 1970s but were not registered in turfgrass until the late 1980s and are used both preemergence and postemergence. Common postemergence PPO herbicides include carfentrazone and sulfentrazone, while oxadiazon and flumioxazin are routinely used as preemergence herbicides although each has postemergence activity. The most unique attribute of oxadiazon is that it does not prohibit lateral spread and recovery of rhizomatous or stoloniferous turfgrasses and can be applied at sprigging of select turfgrass species.

**Table 1** Select herbicide mechanism of action in turfgrass ecosystems and date registered, as sorted by date

| Mechanism of action | Examples of active ingredient(s) | Decade mechanism of action was described or synthesized (not necessarily in turf) | Product registered with US EPA | WSSA/HRAC group number[a] |
|---|---|---|---|---|
| Synthetic auxin mimics | 2,4-D, MCPA, mecoprop, dicamba, clopyralid, fluroxypyr, triclopyr, quinclorac, and halauxifen-ethyl | 1940s | Trimec (1970)<br>Escalade 2 (2005) | 4 |
| Photosystem II inhibitor | Atrazine, simazine, and metribuzin | 1950s | AAtrex (1969)<br>Princep (1973) | 5 |
| Long-chain fatty acid synthesis inhibitor | Ethofumesate and bensulide | 1960s | Prograss (1981) | 15, unknown |
| Protoporphyrinogen oxidase inhibitor | Carfentrazone, flumioxazin, oxadiazon, and sulfentrazone | 1960s | Dismiss (2005)<br>Ronstar (1988)<br>SureGuard (2003) | 14 |
| 7,8-dihydropteroate synthetase inhibitor | Asulox | 1970s | Asulam (1975) | 18 |
| Acetyl CoA carboxylase inhibitor | Fenoxaprop, fluazifop, sethoxydim, pinoxaden | 1970s | Acclaim (1988)<br>Fusilade II (1995)<br>Manuscript (2018) | 1 |
| Cellulose biosynthesis inhibitor | Indaziflam, isoxaben | 1970s | Gallery (1989)<br>Specticle WP (2010) | 29 |
| Microtubule assembly inhibitor | Pendimethalin, prodiamine, and dithiopyr, pronamide | 1970s | Barricade (1992)<br>Pendulum (1990) | 3 |

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| | | | | |
|---|---|---|---|---|
| Acetolactate synthase inhibitor | Flazasulfuron, foramsulfuron, halosulfuron, imazosulfuron, metsulfuron, rimsulfuron, sulfosulfuron, trifloxysulfuron, imazapic, imazaquin, penoxsulam, pyrimisulfan, thiencarbazone | 1980s | Image (1989)<br>Katana (2009)<br>Manage (1994)<br>Manor (1999)<br>Monument (2003)<br>Revolver (2003)<br>TranXit (2001) | 2 |
| Carotenoid biosynthesis inhibitor | Mesotrione, topramezone | 1980s | Pylex (2012)<br>Tenacity (2007) | 27 |
| Fatty acid thioesterase inhibitor | Methiozolin | 1980s | PoaCure (2019) | 30 |

[a]According to Weed Science Society of America Herbicide Site of Action Classification List (Weed Science Society of America, 2021).

Acetyl CoA carboxylase (ACCase)-inhibiting herbicides are commonly referred to as graminicides and were initially synthesized in the 1970s. ACCase herbicides, including fenoxaprop, fluazifop, clethodim, and sethoxydim, were registered in the 1980s and 1990s and possess selectivity in various turfgrass species, while pinoxaden was registered in 2018. Another agronomically important mechanism of action is microtubule assembly-inhibiting herbicides, including pendimethalin, prodiamine, dithiopyr, and pronamide, which were developed in the 1970s although not registered in turfgrass systems until the 1990s and remain important today for annual grass and small-seeded broadleaf weed control. Acetolactate synthase (ALS)-inhibiting herbicides were developed and registered in the 1980s and have multiple active ingredients used predominantly in warm-season turfgrasses for postemergence broadleaf and annual bluegrass (*Poa annua* L.) control and sedge (Cyperaceae) control in warm- and cool-season turfgrass. ALS-inhibiting sulfonylurea herbicides were known for 'revolutionizing' the herbicide industry as they possess high biological activity at low application use rates, which is a favorable trait among regulatory agencies (Waltz and Murphy, 2004) and has been an attribute of many herbicides registered recently. Although herbicidal activity at very low rates is viewed as a positive attribute, it can also be problematic due to off-target damage, as observed with the synthetic auxin herbicide aminocyclopyrachlor in 2011 (Patton et al., 2013a).

Other recently registered herbicides include mesotrione and topramezone (carotenoid biosynthesis inhibitors), indaziflam (cellulose biosynthesis inhibitor), and methiozolin (fatty acid thioesterase inhibitor) (Brabham et al., 2021). Mesotrione and topramezone were registered in 2007 and 2012, respectively, and constitute a major mechanism of action for grass and broadleaf weed control, primarily in cool-season turfgrasses. Indaziflam is the most recently registered preemergence herbicide (2010). Although it is not a new mechanism of action, it is critical for annual bluegrass resistance management in warm-season turfgrass systems. Similarly, methiozolin was registered in 2019 but was not a new mechanism of action.

## 1.2 Problems with relying too much on herbicides for weed control

Herbicides are effective tools for weed management, but there are consequences when turf managers rely on them as the primary control strategy. The primary consequence of relying entirely on herbicides for weed control is that the practice selects for plants that have evolved mechanisms to survive the application or repeated exposure to the herbicide active ingredient(s). Over 513 unique cases of herbicide resistance have been documented throughout agriculture, affecting over 267 different weed species and 21 of the 31 known

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physiological sites targeted by herbicides (Heap, 2022). The rapid onset of herbicide resistance in agricultural systems has revived interest in nonchemical practices to augment herbicide use including crop rotation, tillage, and the use of cover crops after harvest. In turfgrass, these nonchemical practices are often referred to as cultural controls.

Resistance to PSII-inhibiting herbicides was first identified in turf in Mississippi in 1996 (Kelly et al., 1999). Resistance to dinitroaniline herbicides has increased rapidly since 2010, especially in grassy weeds such as annual bluegrass and goosegrass (*Eleusine indica* [L.] Gaertn) particularly on golf courses (Brosnan et al., 2020a,d), and resistance to the pyridine herbicide dithiopyr was also recently identified in goosegrass (Elmore et al., 2022a; Russell et al., 2022). The development of herbicide-resistant weeds is problematic and needs to be addressed, but there are fortunately several factors unique to turfgrass systems that have reduced the evolution of herbicide resistance to date. Patton et al. (2018b) note nine factors that help to reduce herbicide resistance development in turf: (1) applying herbicide premixtures, (2) using grass species known to create dense swards to outcompete germinating weeds, (3) fertilizing to promote increased turf density and reduced weed competition, (4) applying herbicides in high spray volumes to optimize spray coverage, (5) removing tough-to-control weeds by hand-weeding, (6) mowing to decrease weed seed production, (7) harvesting grass clippings and inflorescences to reduce the weed seedbank, (8) reducing soil cultivation to minimize turf injury and recruitment of buried seed, and (9) using preemergence herbicides to prevent weed seed emergence.

For turfgrass managers, the consequence of developing resistant weed populations has been exacerbated in recent years by slowed herbicide discovery efforts amongst agrochemical manufacturers. This began with industry consolidation in the mid-1980s and further slowed by the adoption of transgenic cropping systems in the mid-1990s which reduced the need for additional active ingredients and mechanisms of action (Duke, 2012; Duke and Dayan, 2022). The cost to develop and register new herbicides has also increased. The last new herbicide mechanism of action was carotenoid biosynthesis inhibitors discovered in the 1980s (Beaudegnies et al., 2009). The onset of herbicide-resistant weeds has somewhat reinvigorated herbicide development, although innovations are primarily developed for major agronomic grass crops (e.g. maize, wheat, barley, and rice) and are typically commercialized in these crops for several years before they are registered for the turfgrass market. Exceptions include aminocyclopyrachlor, dithiopyr, ethofumesate, indaziflam, and methiozolin, among others, which were first registered in turfgrass and/or other specialty crop systems.

There may be novel mechanisms of action to aid turfgrass weed management in the future, but identifying new herbicide targets is quite challenging. An alternative approach, such as using natural products and pharmaceutical inhibitors to inspire new herbicides, may be useful, particularly when coupled with artificial intelligence to better understand the structural dynamics of new protein targets in plants (Duke and Dayan, 2022). Cyclopyrimorate (WSSA Group 33) and tetflupyrolimet (WSSA Group 28) represent two new herbicidal active ingredients that are now recognized by the Herbicide Resistance Action Committee as of 2021 (Duke and Dayan, 2022; HRAC, 2022). However, history suggests it will be several years until these products are tested for potential use in turfgrass.

## 2 Current knowledge and future outlook for integrated weed management strategies

Current methods, tactics, and tools for integrated turfgrass weed management include the use and optimization of synthetic herbicides, the use of organic and alternative herbicides including biologicals, physical weed management, cultural practices, improved turfgrass genetics, and the use of remote sensing and artificial intelligence in weed control programs.

### *2.1 Optimizing synthetic herbicide efficacy*

For tough-to-control weeds, optimizing herbicide efficacy is important. This section will discuss strategies that optimize herbicide efficacy against the weeds directly and not consider their effect on the turfgrass sward (to be discussed later in the chapter) which can indirectly enhance herbicide efficacy.

Tank mixing herbicides (e.g. combining two more herbicide products in the same spray solution) to improve weed control or reduce injury to desirable turfgrass is a common strategy. For example, in cool-season turfgrass, annual bluegrass control is difficult to achieve with herbicides. Certain tank mixtures and programs can improve annual bluegrass control, but complete annual bluegrass control using herbicides alone is unlikely in cool-season turfgrass with current herbicide options. Combinations of preemergence and postemergence herbicides (Reicher et al., 2017), low-rate sequential application programs (Jeffries et al., 2013; Skelton et al., 2012), and tank mixtures of mesotrione + amicarbazone (Elmore et al., 2022b) can improve annual bluegrass control, but efficacy is consistently inconsistent across geographic locations and years. To better understand inconsistencies in annual bluegrass control in both cool- and warm-season turfgrass, future research should document management practices [e.g. irrigation, fungicides, and nitrogen (N) fertilizer] that promote or prevent summer annual bluegrass decline as well as the growth habit of annual bluegrass plants at the site using descriptions in Carroll et al. (2021b; i.e. creeping habit characteristic of *Poa*

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*annua* var. *reptans* [Hausskn.] T. Koyama, or upright habit characteristic of *Poa annua* subsp. *erecta*).

The most consistent chemical control of annual bluegrass involves paclobutrazol or flurprimidol application at 2- to 4-week intervals from annual bluegrass seedhead shatter until first frost (Diehl et al., 2021; Jeffries et al., 2013; McCullough et al., 2005; Patton et al., 2019a; Reicher et al., 2017; Woosley et al., 2003). The requirement for frequent applications limits practicality on many turf areas. Another drawback is frequent paclobutrazol or flurprimidol application can select for dollar spot (*Clarireedia* spp.) disease developing insensitivity to other demethylation inhibitors, including fungicides which are important tools for disease management (Allan-Perkins et al., 2017).

Methiozolin, recently registered as PoaCure® for annual bluegrass control, is a new tool for selective annual bluegrass control in cool-season turfgrass, particularly creeping bentgrass putting greens. Unlike other herbicides for annual bluegrass control that were briefly registered for use on putting greens before bentgrass injury issues prevailed, field research indicates methiozolin programs provide annual bluegrass control with little to no creeping bentgrass injury (Askew and McNulty, 2014; Brosnan et al., 2013; Koo et al., 2014; Patton et al., 2019a; McCullough et al., 2013; Xiong et al., 2015). Interestingly, the mechanism for selectivity of annual bluegrass in creeping bentgrass is not well understood, as absorption, translocation, and metabolism do not clearly explain differences in species tolerance (Flessner et al., 2013; McCullough et al., 2013; Yu and McCullough, 2014) and suggests that the deeper and more robust root system of creeping bentgrass that may play a role in selectivity (Brabham et al., 2021).

In warm-season turfgrass, use restrictions on the relatively broad-spectrum herbicide monosodium methanearsonate require the use of alternative, suboptimal herbicides for weed control. For example, the herbicide topramezone is by far the most effective herbicide for goosegrass control, but it also causes dramatic foliar bleaching of most warm-season turfgrass species. Strategies to reduce bleaching but maintain weed control efficacy include tank mixing with various herbicides (Brewer et al., 2022a,b; Carroll et al., 2021a; Cox et al., 2017; Gonçalves et al., 2021), chelated iron (Boyd et al., 2021), and irrigating immediately after application (Brewer et al., 2022b; Kerr et al., 2019). These strategies often reduce goosegrass control, and none eliminate bleaching of desirable turfgrass.

N fertilization at the time of herbicide application can improve weed control. N fertilizer rates as low as 12 kg N•ha$^{-1}$ enhanced the efficacy of postemergence herbicides mesotrione and topramezone for both crabgrass (*Digitaria* spp.) and annual bluegrass (Beck et al., 2015; Elmore et al., 2012, 2013a). While ammonium sulfate is often tank mixed with herbicides to improve absorption, N fertilizer was applied to the soil in these experiments, which suggests that weed control was improved by mechanisms other than increased foliar herbicide absorption. Similar work using higher N rates (73 kg N•ha$^{-1}$) found that N applied just before flazasulfuron application improved annual bluegrass control, which was attributed to increased herbicide translocation (Brosnan et al., 2010). These studies found enhanced herbicide efficacy independent of competition from desirable turfgrass, and the effect may be greater in situations where turfgrass vigor is enhanced by N.

Seasonal application timing can improve herbicide efficacy for perennial weed control. While it is generally understood that immature annual weeds are easier to control, mature perennial weed control can be improved if herbicide applications are made at certain times of the year. Herbicides are most effective for warm-season weeds such as dallisgrass (*Paspalum dilatatum* Poir.) and common bermudagrass (*Cynodon dactylon* [L.] Pers.) at certain temperature-based growing degree-day (GDD) thresholds in the spring and cooling degree-day thresholds in the late summer or early autumn (Brosnan et al., 2011; Elmore et al., 2013b; Johnston and Henry, 2016). For perennial broadleaf weeds, fall applications after first frost are generally considered more effective than spring applications, but some of this is based on research that did not include spring applications for comparison (Kohler et al., 2004; Reicher and Weisenberger, 2007). Fall applications tend to be more effective, but for tough-to-control weeds such as ground ivy (*Glechoma hederacea* L.) herbicide selection is more important (Patton et al., 2017a). Proper spring application timing is also important as auxin mimic herbicides can be less effective against dandelion if made earlier than 135 GDD in the spring or during peak bloom (Raudenbush and Keeley, 2014; Schleicher et al., 1996). The ALS-inhibiting herbicide florasulam should be applied before 75 GDD in the spring for optimum dandelion control (Patton et al., 2018a). Early postemergence applications (200 to 250 GDD) are optimal for yellow nutsedge (*Cyperus esculentus* L.) control (Li et al., 2021).

Other factors important to optimize herbicide efficacy include ensuring the target weed is not drought stressed at the time of application (Shekoofa et al., 2020) and avoiding antagonism of ACCase and phenoxy herbicides (Dernoeden and Fidanza, 1994), or of weak acid herbicides by hard water (Schortgen and Patton, 2021). Failing to include adjuvants can dramatically reduce weed control from many herbicides including ALS inhibitors, carotenoid biosynthesis inhibitors, and quinclorac (Zawierucha and Penner, 2001). Anecdotally, a large proportion of practitioners do not fully comprehend when to include or exclude adjuvants with herbicides. Practitioners often indicate that the adjuvant was not available or not suggested by the salesperson at the point of purchase, or the adjuvant was included even though the product label indicates it should not be included (e.g. herbicides that contain PPO herbicides).

## 2.2 Synthetic herbicide safety and reducing dislodgeable residue

Regulatory agencies (e.g. US EPA) require registrants to conduct comprehensive testing to ensure herbicides do not adversely affect human or environmental health. There are many environmental and toxicological tests required for herbicide registration and reregistration, including tests to characterize environmental fate, residue, and potential off-target movement. In agronomic crops, tolerances are derived from comprehensive risk assessments establishing a maximum amount of a pesticide allowed in or on a food which is commonly referred to as maximum residue limit. These limits are based on multiple factors including the toxicity of the pesticide and metabolites, how much of the pesticide remains in or on food, as well as all potential exposure routes. Other priority areas for herbicide residue concerns revolve around environmental impacts, specifically off-target movement and subsequent damage to neighboring plant or animal species or natural resources. Herbicide registration and reregistration require extensive testing and are only allowed registration if certain criteria are met, ensuring they do not contaminate air, groundwater, and other water bodies or otherwise compromise environmental and/or human health.

In turfgrass ecosystems, herbicide residue concerns are much different compared to food and fiber crops and other cropping systems. In turfgrass ecosystems, concern about herbicide residue focuses on worker and nonworker exposure, residue in turfgrass clippings (e.g. which may be used in composting), and other environmental aspects including how long an herbicide persists as well as its mobility off-target at any time after the application. Specifically, human pesticide exposure for nonworkers in turfgrass systems may occur by multiple routes, including transfer from treated vegetation onto humans as well as multiple indirect routes. Similar to pesticide residue in agronomic crops, comprehensive human herbicide exposure risk assessments must be conducted prior to herbicide registration and reregistration to ensure adverse health effects do not occur following exposure to treated turfgrass areas. Within the occupational and residential exposure tests required by US EPA, foliar transferable residue dissipation studies are required to quantify herbicide residue on treated turfgrass surfaces that may be transferred via non dietary ingestion onto human skin or clothing as well as inhaled (e.g. dust or vapor). Otherwise stated, how much of an applied pesticide is dislodged or transferred to workers or nonworkers at various times after the application? These data are entered into risk models to ensure people are not exposed to adverse effect levels or concentrations. Select herbicides contain verbiage on product labels to address herbicide residue remaining in turfgrass clippings and if they can cause adverse effects. For example, clopyralid can persist in composted clippings, and the compost with clopyralid residue can damage sensitive plants. Dithiopyr and quinclorac have similar label verbiage, indicating that clippings should not be collected from treated areas soon after application to prevent off-target herbicide movement via clippings.

Various factors influence dislodgeable herbicide residue from treated turfgrass surfaces. Product formulation, irrigation, spray application parameters including application water carrier volume and adjuvant or surfactant inclusion, and turfgrass species among other factors influence dislodgeable herbicide residue in turfgrass ecosystems. Specifically, Thompson et al. (1984) reported that liquid 2,4-D, which is highly water-soluble and subject to dislodge, was 15-fold more dislodgeable than granular applications following application. When liquid 2,4-D was used, only <0.01% of applied 2,4-D was dislodgeable 1 day after a rainfall event. In the absence of rain, dislodgeable 2,4-D foliar residues consistently decreased after the application, as small amounts of 2,4-D were detected at 7 days after treatment but none detected beyond 12 days after treatment (Jeffries et al., 2016). Increasing application water carrier volume and spray droplet size can also decrease dislodgeable 2,4-D foliar residue from treated turfgrass surfaces. Specifically, dislodged 2,4-D decreased more than 25% when applied at 748 L•ha$^{-1}$ compared to 187 L•ha$^{-1}$ (Jeffries et al., 2017). Including a nonionic surfactant also reduced dislodgeable 2,4-D foliar residue (Maxwell et al., 2018). Time of day also influences dislodgeable foliar residue; specifically, 2,4-D dislodgeability consistently decreased from morning to afternoon, mostly due to canopy moisture (Jeffries et al., 2016). Therefore, it is possible that dislodgeable herbicide residues from turfgrass can be dramatically reduced with coordination between turf managers and scheduled events at the turf site.

## *2.3 Organic and alternative herbicides*

Due to public concern over pesticide exposure, governments and other policymakers have severely restricted or banned pesticide use on school grounds and public areas in North America (Campbell and Wallace, 2020). Quebec, Canada, passed the Pest Control Products Act in 2003 that resulted in the ban on selling pesticides for use in lawns, including the herbicide 2,4-D (Conlin, 2008). The herbicide 2,4-D was included in the Quebec ban for precautionary reasons despite uncertain evidence about its effects on human health (Conlin, 2008). Thorough reviews of 2,4-D toxicology report 'no evidence that 2,4-D poses any health risk to humans' and 'no convincing or consistent evidence for any chronic adverse effect of 2,4-D in humans' (Burns and Swaen, 2012; Kennepohl et al., 2010). Ironically, in 2011, as part of a settlement with Dow AgroSciences (Indianapolis, IN, USA), the government of Quebec agreed that 'products containing 2,4-D do not pose an unacceptable risk to human health or the environment' (Dow AgroSciences LLC vs. Her Majesty the Queen in Right of Canada, 2011). Despite this declaration in 2011, Quebec did not remove 2,4-D from its list of banned pesticides. Later, Ontario, Canada, followed Quebec and outlawed the use of pesticides on lawns, gardens, hardscapes, cemeteries, parks, and schoolyards (Ontario Ministry of the Environment, 2009). Most recently, Montgomery County, MD, USA, passed legislation that bans the use of pesticides in public and private lawns (Janasie, 2019). Increasing regulation of pesticide use in turfgrass systems and an ever-increasing interest from the public on 'natural' or 'organic' products for weed control has resulted in a demand for organic and alternative herbicides. While these pesticide bans result in reductions in turfgrass and ground quality, especially in lower income areas, they are popular and will likely continue and be implemented by an increasing number of policymakers (Bartholomew et al., 2015).

Pesticide bans enacted by governments and policymakers provide a defined list of products permitted for use. The pesticide bans often allow exemptions for certain Organic Materials Research Institute (OMRI; https://www.omri.org)-approved horticultural oils and soaps as alternatives. Outside of these examples of legislation, defining what is permitted in a 'natural' and 'organic' program is difficult as the USDA National Organic Program is for agricultural products only. Currently, there are no federal standards for organic turfgrass management and no restrictions on using the word 'organic' by turfgrass practitioners. The Northeast Organic Farming Association of Connecticut (NOFA; https://ctnofa.org) established standards and an accreditation program for Organic Land Care in Connecticut, USA, which includes lawn management. Interestingly, the NOFA organic land care program allows for 'emergency non-organic rescue treatment' in extenuating circumstances and notification of the property owner. The use of a synthetic pesticide results in a property being designated as 'transitional', but the implications of the transitional designation nor the length of time it is designated transitional are not discussed (NOFA, 2017). This program also permits the use of conventional sod and seed.

There are multiple categories of products considered natural or organic. A category of products considered low risk is exempt from US EPA registration under the Federal Insecticide, Fungicide, and Rodenticide Act section 25(b). Another category includes products with a US EPA registration number and further certification status from organizations such as OMRI. This includes natural products and certain synthetic materials in Title 7 Code of Federal Regulations (CFR) 205.601. A third category is products marketed as natural or organic but do not have 25(b) exempt status and are not OMRI approved. Regardless of the category, nearly all the products are nonselective postemergence herbicides that destroy the cuticle layer and disrupt the cell membrane permeability but do not translocate. In cool-season turfgrass, these products cause severe injury to desirable turfgrass, and single applications do not provide weed control (Patton et al., 2019b). An initial investigation by Flessner et al. (2010) indicates these products have potential for weed control in dormant bermudagrass. Unlike many alternative products, chelated iron (Fe-HEDTA) is selective for broadleaf weeds in turfgrass (Patton et al., 2019b). While chelated iron products do not have 25(b) exempt status, they are often permitted where synthetic pesticides have been banned, including Ontario, Canada, and Montgomery County, MD, USA (Ontario Ministry of the Environment, Conservation and Parks: https://www.ontario.ca/page/using-pesticides-ontario; Kao-Kniffen, 2020).

Corn gluten meal is an organic preemergence herbicide widely sold for crabgrass control. Commonly used as an animal feed, corn gluten meal is the protein fraction of corn extracted during the wet milling process and contains 10% N by weight. A similar product, corn gluten hydrolysate, is derived from corn gluten meal and is slightly more effective in controlled environments (Liu et al., 1994). Despite widespread usage, demonstrated corn gluten meal efficacy in field studies at the recommended rate (980 kg•ha$^{-1}$) with N fertilizer standards for comparison is limited to one study which found that two sequential applications at 730 kg•ha$^{-1}$ provided some smooth crabgrass control (Dernoeden, 2001). Other work that included a fertilizer standard and corn gluten meal at registered use rates found that corn gluten meal and fertilizer standards provided similar weed control (Christians and Dant, 2005; St. John and DeMuro, 2013). The recommended corn gluten meal rate provides 98 kg N•ha$^{-1}$, which exceeds the legal nutrient application limit in some states in the USA. Controlled environment research suggests that efficacy is dependent on a drought period shortly after weed emergence, and the most effective rates are higher than practical due to cost and excessive N fertilizer rate (Gardner et al., 1997; Liu and Christians, 1997). Efficacy may also depend on applying the product within 1 week prior to crabgrass germination (Christians, 1993). Interestingly, Gardner et al. (1997) found that corn gluten meal improved the efficacy of low rates of pendimethalin, but an N fertilizer standard was not included in the study. Corn gluten in combination with low rates of pendimethalin or other mitotic inhibiting herbicides would be an interesting area for further research since the primary mechanisms of action are similar (Unruh et al., 1997).

## 2.4 Biological herbicides

There are promising biological control agents in development for use in turfgrass, some even commercialized for a short period, but none are currently available. These efforts use the inundative or bioherbicide strategy where bacteria or fungi are applied at concentrations far exceeding those found naturally rather than the classical biological approach of releasing the organism to persist in the environment for a long period of time. While these agents often show promise in controlled environments and field research, they often fail commercially due to narrow weed control spectrum, high production costs, and specific environmental conditions required for efficacy (Watson and Bailey, 2013). The fungus *Sclerotinia minor* demonstrated moderate efficacy for dandelion control under specific environmental conditions and was sold as Sarritor in Canada (Abu-Dieyeh and Watson, 2007a,b). However, after just 1 year of commercialization, the introduction of Fe-HEDTA eliminated demand for Sarritor, and it is no longer commercialized (Watson and Bailey, 2013). More promising, a strain of *Phoma macrostoma* with broad-spectrum activity on dicots and safety to monocots was registered in Canada and the USA in 2011 and 2012, respectively, but the partnership of Agriculture and Agri-Food Canada (Ottawa, Ontario, Canada) with The O.M. Scotts Company (Marysville, OH, USA) did not result in a commercial product (Bailey and Falk, 2011; Bailey et al., 2011). Development of bacteria for biocontrol is a similar story of promising efficacy with no commercialized products. A *Pseudomonas fluorescens* isolate with proven cheatgrass (*Bromus tectorum* L.) control in large-scale multiyear field experiments was released commercially in agriculture for a short time (Kennedy et al., 1991). As part of this project, another *P. fluorescens* isolate was developed for annual bluegrass control in turfgrass (Kennedy, 2016) but never commercialized, despite field development efforts from the commercial sector. Similarly, a *Xanthomonas campestris* isolate for annual bluegrass control in creeping bentgrass (*Agrostis stolonifera* L.) was registered for a short time in Japan, but is no longer available (Imaizumi et al., 1997; Nishino and Tateno, 2000).

A biocontrol strategy that does not require introduction of a foreign agent uses the annual bluegrass weevil (*Listronotus maculicollis* Kirby) insect to control annual bluegrass. This insect is a common pest of golf course turfgrass in the northeastern USA and in Ontario, Canada. The annual bluegrass weevil larvae cause more damage to annual bluegrass than creeping bentgrass (Kostromytska and Koppenhöfer, 2014, 2016). Delaying insecticide applications until the weevil larvae cause substantial damage to the annual bluegrass can reduce annual bluegrass populations in golf course fairways. Using this biocontrol strategy in combination with the plant growth regulator paclobutrazol improves the annual bluegrass control compared to either strategy alone (Diehl et al., 2021, 2022).

Biopesticide sales increased from 2.4% of the crop protection market in 2009 to 5.0% in 2017 (Baker et al., 2020). If investment in developing biological options increases similarly, or legislation forces rapid change, effective options may be on the horizon. Future development should focus on finding bioherbicides that can reduce rates of synthetic pesticides or be combined with cultural management practices to provide commercially acceptable control instead of expecting the product to perform similarly to synthetic products alone. Given the price sensitivity toward synthetic pesticides, golf courses, athletic fields, and lawn care business models with less price sensitivity could be targeted for early adoption of these bioherbicide products. Golf courses and athletic fields with on-site managers are also better able to time biopesticide applications with proper environmental conditions often required for efficacy.

Lastly, fungal endophytes may confer indirect biological control of weeds. Several *Epichloë* spp. endophytic fungi exist in a mutualistic relationship with the host plant, providing important abiotic (e.g. drought) and biotic stress (e.g. disease and insect) tolerance (Funk et al., 1993). This host-plant resistance to stresses is conferred through the production of defensive alkaloids and antifungal proteins (Baldauf et al., 2011; Tian et al., 2017). While there is no direct evidence that the resulting changes in turfgrass physiology as a result of endophyte infection externally influence the germination or emergence of weeds, the host-plant resistance conferred by the endophytes does result in reduced stress to the turfgrass, which should lead to the maintenance of a dense sward and a subsequent reduction in weed recruitment. This concept merits further study.

## 2.5 Physical weed management

Optimal weed management programs are designed to reduce the overall abundance of existing weed seed in the soil profile, often termed the weed 'seedbank' as well as to limit the deposition of new weed seed into the soil (Norsworthy et al., 2018). In turfgrass management, practices such as fraise mowing and clipping collection after mowing can be implemented with this in mind. Fraise mowing is a turfgrass cultivation practice that removes aboveground biomass allowing swards to regrow from belowground vegetative tissue (Brosnan et al., 2020b). Research has shown that the debris removed during fraise mowing contains an abundance of weed seed. For example, debris generated after fraise mowing a zoysiagrass (*Zoysia japonica* Steud., 'Meyer') fairway contained seed from numerous winter and summer annual weed species, and 59% of those seeds were winter annual broadleaf species and 28% were annual bluegrass (Brosnan et al., 2020b). Summer fraise mowing bermudagrass (*Cynodon* spp.) resulted in 41% to 97% reductions in annual bluegrass the following spring; however, turfgrass managers identified numerous barriers to adopting this practice, including cost, labor, area closure, and debris removal (Carroll et al., 2021c).

These barriers may also prevent the adoption of flaming for weed control in turfgrass (Fig. 2). This practice can be selective as perennial turfgrasses can regrow from rhizomes or stolons after the aerial portions are killed by flaming. Using a flamer powered by liquefied petroleum gas in the spring provided moderate weed control in hybrid bermudagrass and seashore paspalum,

**Figure 2** A flame treatment on cool-season turfgrass caused unacceptable cool-season turfgrass injury for more than 4 weeks and provided <50% weed control (Patton et al., 2019b).

but >70 kg•ha$^{-1}$ of liquefied petroleum gas was required for weed control and 3 weeks was needed for the bermudagrass to recover from flaming (Martelloni et al., 2018, 2019). Flaming may have potential for weed control before cool-season turfgrass establishment from seed. Tillage, followed by flaming after weed seedling emergence but prior to tall fescue (*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* [Schreb.] Dumort., nom. cons.) seeding, controlled several summer annual weed species as well as the fumigant dazomet (Hoyle et al., 2012), but was less effective than dazomet at removing perennial weeds (Patton et al., 2019b).

For selective mechanical broadleaf weed control without severe turfgrass injury, a device called the Weedbine is in development (Henderson, 2021). This device modifies the cutting unit on a triplex reel mower, removing the cutting reel and replacing it with a coarse brush. The bedknife is replaced with a grooved baseblade (Fig. 3). As the bristles pass through the grooved baseblade, the broader leaved plants are removed or severely injured while the narrower leaved monocots are less injured. Using the Weedbine once per week during the growing season provided dandelion and white clover control comparable to a synthetic herbicide program and similar or improved turfgrass quality compared to synthetic herbicide programs (Henderson, 2021).

On putting greens, clipping collection over a 2-year period has been shown to reduce viable annual bluegrass seed in the soil by 60%, which results in a more modest reduction in annual bluegrass establishment

**Figure 3** Bristles of the coarse brush interacting with the grooved baseblade of the Weedbine. Source: Henderson (2021).

(Gaussoin and Branham, 1989). More commonly, clipping return decreases weed infestations, possibly a result of nutrient return from clippings and providing a light layer of mulch to prevent weed seed germination (Haley et al., 1985; Harivandi et al., 2001; Heckman et al., 2000). Perhaps timing clipping collection to coincide with weed flowering would be most effective and minimize barriers to adopting this practice over large acres of managed turfgrass.

### *2.6 Cultural weed management*

Busey (2003) and Hahn et al. (2020) provide a comprehensive review on the effect of cultural practices such as mowing, N fertilization, irrigation, and cultivation on weed incidence in turfgrass ecosystems. Mowing at the highest height within the recommended range for a particular species and proper N fertilization to promote turfgrass canopy density usually decrease weed incidence. While the effect of mowing height on weed incidence is very powerful, Hahn et al. (2020) noted that most research examined large changes in cutting height instead of small changes in cutting height within practical limitations for usability. Another weakness of previous research is that mowing height treatments are not often accompanied by an increase in fertilizer input, mowing frequency, or other cultural practices that practitioners would employ to increase canopy density at lower mowing heights (Law et al., 2016). Investigations of small changes in cutting height that are not confounded by a reduction in canopy density or increase in turfgrass disease (as noted by Cutulle et al., 2014) would be useful to determine whether certain weeds are more or less adapted to certain mowing heights.

Interseeding turfgrass has utility for weed control, especially where effective herbicides are not available. Frequent interseeding that increases turfgrass cover can provide modest reductions of established perennial weeds such as dandelion and white clover (*Trifolium repens* L.) and annuals such as crabgrass (Elford et al., 2008; Miller and Henderson, 2012). Success of interseeding creeping bentgrass in fine turf where annual bluegrass is dominant is dependent on seeding during mid-summer when annual bluegrass is less competitive (Henry et al., 2005; Murphy et al., 2005).

The influence of cultural practices on annual bluegrass competitiveness has been evaluated more comprehensively than any other weed species, probably due to the ubiquity and cosmopolitan nature of annual bluegrass. Almost all the research evaluating cultural practices has been conducted in cool-season turfgrass where effective herbicide options for control are limited in the USA and nonexistent in Canada and Europe.

Annual bluegrass is more competitive under low mowing heights and greater irrigation. Specifically, greater irrigation frequency more than quantity promotes annual bluegrass infestation (Bell et al., 1999; Cain et al., 2021; Chen et al., 2018; Gaussoin and Branham, 1989; Youngner, 1959). High irrigation frequency is required to maintain annual bluegrass, particularly during the summer when the root system is most shallow and drought stress promotes anthracnose disease to which annual bluegrass is very susceptible (Roberts et al., 2011).

Low soil pH also reduces annual bluegrass competitiveness more so than desirable turfgrasses and has been recommended for annual bluegrass suppression (Goss et al., 1975; Varco and Sartain, 1986). The soil pH effect is thought to be a result of limited phosphorus (P) availability at low soil pH, which reduces annual bluegrass competitiveness more so than desirable turfgrass. This is corroborated by work that found that high elemental sulfur rates (>168 kg•ha$^{-1}$ year$^{-1}$) reduced annual bluegrass on a putting green (Goss et al., 1975; Varco and Sartain, 1986). P requirements in turfgrass systems have been investigated for nearly a century, and annual bluegrass incidence often increases when phosphate fertilizer is applied (Sprague and Burton, 1937). This effect is usually only observed in sand root zones where P is low (<24 mg•kg$^{-1}$ Mehlich-3-P), and in these experiments the lowest phosphate rate is associated with an increase in annual bluegrass compared to no phosphate application, but there is no further increase in annual bluegrass incidence with P rate (Lodge et al., 1990; Øgaard and Aamlid, 2020; Raley et al., 2013; Waddington et al., 1978). From this field research, it is not known whether P application enhances annual bluegrass establishment from seed or the competitiveness of mature plants. Comparing annual bluegrass and creeping bentgrass in monoculture, when no P was applied in a low P soil, creeping bentgrass yield and P uptake were greater than in annual bluegrass; however, as soil P increased (≥40 mg•kg$^{-1}$), annual bluegrass yield and P uptake became superior (Kuo, 1993). However, it is not well understood how annual bluegrass and other turfgrass species compete under various soil P concentrations. Until the influence of P on annual bluegrass competitiveness is understood enough to provide a more defined set of soil test P values that will reduce the competitiveness of annual bluegrass without compromising desirable turfgrass quality, practitioner adoption of P management to reduce annual bluegrass encroachment is unlikely.

N also has significant effects on annual bluegrass encroachment, with higher N rates generally resulting in more annual bluegrass, with the exception being in a turf sward that is thin due to N deficiency. Especially for species like creeping bentgrass or velvet bentgrass (*Agrostis canina* L.) that require limited N, annual bluegrass encroachment is reduced when N is applied sparingly (Skogley, 1975; Tang et al., 2021). The time of year N is applied is also important, with late autumn and early spring applications as well as spoon-feeding N during the summer favoring annual bluegrass (Dernoeden, 2013). The N form is also important as acidifying N sources such as ammonium sulfate tend to favor desirable turfgrass species over annual bluegrass (O'Connor et al., 2018).

Annual bluegrass is more sensitive to high rates of iron (Fe) than creeping bentgrass (Xu and Mancino, 2001). In field studies, Fe has been investigated for annual bluegrass control in creeping bentgrass putting greens with mixed results. In a 2-year study, Han et al. (2017) found that ferrous sulfate applied at 12 $kg \bullet ha^{-1}$ or 49 $kg \bullet ha^{-1}$ nine times annually had a modest effect on annual bluegrass encroachment in a creeping bentgrass putting green. As that study continued 7 more years, the effect of ferrous sulfate was minimal (Tang et al., 2021). Similarly, ferrous sulfate applied six times annually at 50 $kg \bullet ha^{-1}$ in a 4-year, three-location study on creeping bentgrass putting greens provided little to no annual bluegrass control (Patton et al., 2019a). These results contrast with a 2-year study where biweekly applications of ferrous sulfate at 12 $kg \bullet ha^{-1}$ or 49 $kg \bullet ha^{-1}$ showed moderate reductions in annual bluegrass cover (Ervin et al., 2017).

Certain weed species, especially prostrate knotweed (*Polygonum aviculare* L.) and goosegrass, are very competitive in highly trafficked areas on golf courses, athletic fields, and parks. Whether wear tolerance, soil compaction, and lack of turfgrass cover are responsible for weed competitiveness in these areas is unknown. Goosegrass seedling and bermudagrass root and shoot growth were reduced similarly in compacted soils, suggesting that wear tolerance may be the mechanism for the competitive advantage of goosegrass in highly trafficked areas (Arietta et al., 2009). Nevertheless, core cultivation (Turgeon and Fidanza, 2017) is often recommended to reduce weed incidence in highly trafficked areas. Often, there is concern amongst practitioners that core cultivation will increase weed incidence or reduce efficacy of preemergence herbicides. Golf course superintendents try to schedule core cultivation to not coincide with annual bluegrass seedling emergence (Christians, 1996; Dernoeden, 2013). While this is logical, one long-term, multilocation study on the topic found that annual bluegrass incidence did not increase when creeping bentgrass putting greens were core cultivated in summer compared to early fall (Patton et al., 2019a). Information on the effect of cultivation practices (e.g. hollow-tine cultivation and vertical mowing) on weed infestations is often found in experiments where the primary objective was to investigate the efficacy of these practices on thatch removal or preemergence herbicides (Branham and Rieke, 1986; Elmore and Tuck, 2021; Johnson, 1979, 1982; Weston and Dunn, 1985). In the absence of preemergence herbicides, early spring vertical mowing and hollow-tine cultivation were found to increase large crabgrass (*Digitaria sanguinalis* [L.] Scop.), black medic (*Medicago lupulina* L.), and henbit (*Lamium amplexicaule* L.) in plots with poor turf quality that were severely thinned due to cultivation treatments (Johnson, 1979; Weston and Dunn, 1985). Where turfgrass quality was high throughout the experiment, aggressive core cultivation in the spring did not increase annual bluegrass, crabgrass, or goosegrass incidence in the absence or presence of preemergence herbicides (Branham and Rieke, 1986; Elmore and Tuck, 2021; Johnson, 1982; Patton et al., 2019a). Where turfgrass is dense and actively growing, evidence suggests that core cultivation should proceed without concern for annual weed encroachment. This is true even if a preemergence herbicide has been applied as core cultivation or vertical mowing do not reduce herbicide efficacy.

## 2.7 Increasing plant competition with weeds through genetics

Turfgrass species selection is a known way to suppress weeds either through a 'right-plant, right-place' approach to making sure the turfgrass species selected is well-adapted to the environment, pests, and management of the site or through enhanced competition with weeds conferred through high plant density or potential allelopathy. DeBels et al. (2012) compared the encroachment of weeds in Kentucky bluegrass (two cultivars), Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin), tall fescue, and perennial ryegrass (*Lolium perenne* L.) over the course of 3 years and while imposing three different mowing heights and three N fertilization programs in Wisconsin. DeBels et al. (2012) noted that dandelion was the most prevalent weed; tall fescue had the fewest weeds and was the only turf species with the same weed cover (3%) regardless of N fertilization rate. Unimproved 'Kenblue' Kentucky bluegrass had more weed cover (15% to 26%) which was not affected by N fertilizer rate (DeBels et al., 2012). Among the species, dandelion cover rankings were Kentucky bluegrass ≥ perennial ryegrass ≥ tall fescue = Chewings fescue. A similar study with multiple species and three mowing heights by Dernoeden et al. (1994) reported that smooth crabgrass and white clover cover were reduced in swards of sheep fescue (*Festuca ovina* L.) and hard fescue (*Festuca brevipila* Tracey) compared to tall fescue when irrigation and fertilizer inputs were withheld. Following 2 years of turf management without herbicides in Virginia (USA), hard fescue resisted weed invasion better than tall fescue (Askew et al., 2013). Overall, the fine fescue taxa are known to have similar or greater resistance to weed invasion than other cool-season turfgrass species (Braun et al., 2020). These experiments primarily highlight the 'right-plant, right-place' approach to reducing weed competition. Refer to Busey (2003) to review specific biotic and abiotic stresses for their effect on weed populations.

Few studies have directly compared warm-season turfgrass species for their ability to suppress encroaching weeds. Among warm-season turfgrass species, zoysiagrass (*Zoysia* spp.) is often noted for its ability to resist weed invasion (Patton et al., 2017b). Weeds are often most problematic amongst warm-season turfgrasses in winter in areas where the turfgrasses are dormant. Winter annual weeds such as annual bluegrass, common chickweed (*Stellaria media* L.), and henbit are often common in winter months. Although the high tiller density of zoysiagrass does not prevent all weeds as some have suggested (Forbes and Ferguson, 1947), zoysiagrass usually has less weed problems than bermudagrass (Patton et al., 2017b).

Plant breeders develop cultivars that have enhanced abiotic and biotic stress tolerance, which leads to improved turf performance, less plant death, and a resulting turf sward that has fewer weeds. Examples might include a bermudagrass cultivar with improved spring dead spot (*Ophiosphaerella herpotricha* [Fr.] Walker) resistance (Baird et al., 1998) that is accompanied by a decrease in weed cover (Fig. 4). Likewise, all turfgrass cultivars with improved abiotic and biotic stress tolerance achieved through plant breeding and improved genetics (or host-plant resistance conferred by endophytes as mentioned previously) should result in a reduction in weed competition. Cultivars can also resist weed invasion through enhanced tiller density. Beard et al. (2001) reported that significant cultural control of annual bluegrass could be gained by selecting cultivars of creeping bentgrass that have a high shoot density under close mowing. The increased density also increases competition and allows fewer opportunities for weed seed recruitment. While improved tiller density will likely ward off weeds in many turf species, a high tiller density may not necessarily prevent weeds, especially perennial weeds. Brede (1992) found that tall fescue cultivars with contrasting density had similar common bermudagrass cover. With tall fescue, the improved cultivar that provided higher turf quality and density did not provide additional perennial weed suppression over a 60+-year-old cultivar. While genetic (cultivar) advancements have been made, their value in weed control has probably been under-researched and thus is not well understood compared to the contribution of improved genetics for gains in drought, disease, or insect pest tolerance.

**Figure 4** A common bermudagrass cultivar with high susceptibility to spring dead spot disease and the subsequent high weed encroachment.

The latest advancement in turfgrass cultivar development related to weed management is the use of biotechnology. The O.M. Scotts Company developed a transgenic Kentucky bluegrass and St. Augustinegrass (*Stenotaphrum secundatum* [Walter] Kuntze) cultivars with both a gene that produces a type of 5-enolpyruvylshikimate-3-phosphate synthase with reduced affinity for glyphosate (Blume et al., 2010; Buhlman et al., 2022; Harriman et al., 2019) and a gene responsible for the overexpression of GA2-oxidase to reduce functional gibberellic acid production, leading to improved sustainability through reduced lawn mowing and related emissions as well as increased shade tolerance (Fidanza et al., 2022; Reed et al., 2021). Several cultivars with these traits were developed and are branded under the names Scotts 'ProVista' (Fidanza et al., 2022). Because of the rapid development of glyphosate-resistant weeds in agricultural fields following the development of glyphosate-resistant crops (Shaner et al., 2012) and because of the current existence of glyphosate-resistant weeds in turfgrass ecosystems, such as annual bluegrass, there is great concern that the development of this technology will hasten the development of herbicide-resistant weed populations. Being mindful of this, the developers of ProVista™ grass varieties encourage the following best management practices to help steward the technology and prevent the development of herbicide-resistant weeds: (1) optimize turf health and quality to reduce the need to apply herbicides, (2) utilize preemergence herbicides for weed prevention, (3) do not rely solely on glyphosate for weed control, (4) rotate herbicide mode of action, and (5) tank mix other herbicides with glyphosate to improve the efficacy on target weeds (Pedersen, 2019). While transgenic genetic crops are now common, transgenic turfgrasses are novel and their value in weed control in turf ecosystems is under-researched and not well understood. Further, while the risk that this technology could lead to the evolution of herbicide-resistant weed populations is clear, it is unclear how quickly this may occur in turf ecosystems as there are fewer reports of herbicide-resistant weeds in turf than agronomic crops due to the previously mentioned factors that make turf ecosystems unique (Mithila et al., 2011; Patton et al., 2018b).

Allelopathy is the 'direct or indirect harmful effect by one plant on another through production of chemical compounds that escape into the environment' (Rice, 1984) (Fig. 5). In turfgrass ecosystems, annual bluegrass, colonial bentgrass (*Agrostis capillaris* L.), fine fescue taxa, Kentucky bluegrass, perennial ryegrass, and tall fescue have all been cited in works describing their ability to suppress weeds through allelopathy (Bertin et al., 2007, 2009; Braun et al., 2020; Breuillin-Sessoms et al., 2021; Buta and Spaulding, 1989; Fales and Wakefield, 1981; Lickfeldt et al., 2001; Lipinska and Sykut, 2012; Peters and Luu, 1985; Smith and Martin, 1994; Walters and Gilmore, 1976; Weston, 1996; Wu et al, 1998; Zuk and Fry, 2005). While there is much discussion about allelopathy, Breuillin-Sessoms et al. (2021) point out that 'this knowledge has not been translated into cultivar development' as no commercial cultivars are

**Figure 5** The potential benefits of allelopathy are evident in this photo where a large patch of quackgrass (*Elymus repens* L.), which has a low tiller density, is excluding weeds compared to the Kentucky bluegrass and perennial ryegrass in this low maintenance lawn.

marketed for their value-added weed suppression. A challenge in perennial cropping systems, such as turfgrass, is separating the plant competition from allelochemical effects. In fact, Lickfeldt et al. (2001) concluded that weed suppression from these turfgrass species was likely due to competition for light, water, and nutrients and not from allelopathy. More recently, Breuillin-Sessoms et al. (2021) concluded that while the weed suppressive ability of some turfgrass species and cultivars can be confirmed, there is still a need to increase our knowledge of how this suppression works. Undoubtedly, turfgrass scientists will continue to study the mechanism of allelopathy with the potential to develop improved cultivars. However, weeds are just one of the pests of turf, and the importance of the 'right-plant, right-place' approach to selecting turfgrass species and cultivars, with both abiotic and biotic stress tolerance, should remain paramount.

### *2.8 Remote sensing and artificial intelligence for weed control*

Spot spraying herbicides instead of broadcasting can dramatically reduce the amount of herbicide needed for weed control. This strategy reduces weed management costs if the spot application process is automated. In row crop agriculture, the See and Spray™ (Blue River Technology; Sunnyvale, CA, USA) system is commercially available for fallow field spraying. Other systems in development also use cameras and artificial intelligence to distinguish between crops and weeds. It is more challenging to detect grassy weeds in turfgrass than row crops as the grassy weeds and desirable turf have similar morphology and are intermixed, but recent work found that convolutional neural networks can detect grassy and broadleaf weeds from photographic images in both actively growing and dormant bermudagrass (Yu et al., 2019, 2020). With neural networks capable of detecting weeds in turfgrass, this technology could be coupled with a camera and sprayer system for field use. However, a commercially available system for spot spraying weeds in turfgrass is likely years away. It is unknown if any system exists in the late stages of development for weed control in turfgrass though there are considerable efforts underway in using remote sensing for early detection of abiotic stress and disease (Badzmierowski et al., 2019; Booth et al., 2021).

## 3 Current knowledge of integrated chemical and nonchemical management

Given the efficacy of chemical weed control, research that investigates herbicides or plant growth regulators to improve efficacy of nonchemical management practices will be the focus of this section. A summary of recent research integrating chemical and nonchemical practices for weed control can be found in Table 2. Compared to studies that examined chemical management alone, there have been surprisingly few studies that evaluate the effect of nonchemical methods in combination with chemical methods.

Several projects have investigated annual bluegrass control in creeping bentgrass putting greens. A 9-year study investigated how N rate, ferrous sulfate, and plant growth regulators affect annual bluegrass on a creeping bentgrass putting green. At the conclusion of year 2 of the study, flurprimidol reduced annual bluegrass cover from 43% to 8% with a low N program (24 kg N•ha$^{-1}$ annually) but was less effective in the high N program (108–147 kg N•ha$^{-1}$ annually) where annual bluegrass cover was 21% (Han et al., 2017). In years 3 through 9 of the study, flurprimidol was effective regardless of N program, although the high N program dramatically increased annual bluegrass cover when trinexapac-ethyl or no plant growth regulator was applied (Tang et al., 2021). Ferrous sulfate applied at 49 kg•ha$^{-1}$ nine times annually resulted in a modest reduction in annual bluegrass cover with the low N program but was not effective in reducing annual bluegrass with the high N program in the first 2 years of the study (Han et al., 2017). In subsequent years, under the low N program, ferrous sulfate did not reduce annual bluegrass cover (Tang et al., 2021). Plant growth regulator programs muting effects of nonchemical management strategies were also reported by Ervin et al. (2017) and Diehl at el. (2021). Future annual bluegrass research should evaluate chemical management programs that would be moderately effective alone to determine whether they can be enhanced by nonchemical management. For example, Diehl et al. (2022) found that lower rates of paclobutrazol could be used for annual bluegrass control in a creeping bentgrass fairway when combined with the annual bluegrass weevil biocontrol.

Another biocontrol agent *S. minor* was moderately effective for dandelion control when applied alone. When cool-season turfgrass was seeded 10 days after *S. minor* application, dandelion cover was reduced by >90%, compared to 60% to 70% for *S. minor* alone. Seeding alone did not reduce dandelion cover (Abu-Dieyeh and Watson, 2007b).

Controlling perennial warm-season weeds such as dallisgrass and bermudagrass typically requires sequential herbicide applications. In research simulating lawn care scenarios, tall fescue interseeding in late summer or early autumn combined with herbicide programs increased control of warm-season perennials bermudagrass, dallisgrass, and false-green kyllinga (*Kyllinga gracillima* Miq.) compared to either practice alone. Three sequential applications of topramezone herbicide provided ≤50% bermudagrass control, which would be considered commercially unacceptable. When tall fescue was interseeded 3 weeks after the final topramezone application, bermudagrass was controlled 88% to 92% (Brosnan and Breeden, 2013). Moderately effective

**Table 2** Recent research (within the last 20 years) integrating chemical and nonchemical strategies for weed management in turfgrass

| Weed | Turfgrass species | Nonchemical practice | Herbicide, plant growth regulator, or biological agent | Findings | Reference |
|---|---|---|---|---|---|
| Annual bluegrass (*Poa annua*) | Creeping bentgrass (*Agrostis stolonifera*) (fairway) | Annual bluegrass weevil (*Listronotus maculicollis*) biocontrol | Plant growth regulator (paclobutrazol) | Allowing annual bluegrass weevil to cause damage combined with paclobutrazol controlled annual bluegrass more than either practice alone. | Diehl et al. (2021, 2022) |
| Annual bluegrass | Creeping bentgrass (putting green) | Low or high nitrogen (N) fertilizer regimen | Plant growth regulators (trinexapac-ethyl and flurprimidol) | Annual bluegrass cover was lowest at low N with flurprimidol. High N dramatically increased annual bluegrass cover in the absence of flurprimidol. A ferrous sulfate program was also evaluated but had little effect. | Han et al. (2017), Tang et al. (2021) |
| Annual bluegrass | Creeping bentgrass | Two core aerification timings | Eight treatments consisting of nutrients, herbicides, or plant growth regulators | Aerification timing did not influence annual bluegrass control. | Patton et al. (2019a) |
| Annual bluegrass | Creeping bentgrass | Biweekly ferrous sulfate application | Biweekly plant growth regulator paclobutrazol application | Ferrous sulfate reduced annual bluegrass alone but did not enhance paclobutrazol efficacy, likely because paclobutrazol was extremely effective alone. | Ervin et al. (2017) |
| Annual bluegrass | – | N fertilizer | Postemergence herbicide flazasulfuron | Flazasulfuron controlled annual bluegrass more when 73 kg N•ha$^{-1}$ was applied prior to herbicide application and again 4 weeks later (150 kg N•ha$^{-1}$ total). | Brosnan et al. (2010) |

(*Continued*)

**Table 2** *(Continued)*

| Weed | Turfgrass species | Nonchemical practice | Herbicide, plant growth regulator, or biological agent | Findings | Reference |
|---|---|---|---|---|---|
| Common bermudagrass (*Cynodon dactylon*) | – | Fraise mowing | Postemergence herbicide glyphosate and glyphosate + fluazifop | Fraise mowing before or after herbicide application improved control compared to either practice alone. | Richardson et al. (2021) |
| Common bermudagrass | Tall fescue (*Schedonorus arundinaceus*) | Fall interseeding | Postemergence herbicide topramezone | Control increased from 27% to 50% with herbicide alone to >85% with seeding. | Brosnan and Breeden (2013) |
| Crabgrass, smooth (*Digitaria ischaemum*) | Tall fescue | Mowing height of 2.5–10 cm | Low rate of prodiamine | Prodiamine was less effective at 2.5 cm mowing height in one study year. Otherwise, mowing height had no effect. | Cropper et al. (2017) |
| Crabgrass (*Digitaria* spp.) | Common bermudagrass | Mowing | Preemergence herbicides | All herbicides provided greater crabgrass control at 3.8 cm mowing compared to 1.5 cm in one of two experiment years. | Gannon et al. (2015) |
| Crabgrass spp. | Tall fescue | N fertilizer | Postemergence herbicides mesotrione and topramezone | N fertilizer applied 3 days, 1 days, and 0 days before herbicide at ≥13 kg•ha$^{-1}$ increases efficacy. | Beck et al. (2015), Elmore et al. (2012) |
| Crabgrass, smooth | Tall fescue | Fungicide to control brown patch disease | Preemergence herbicides pendimethalin, prodiamine, and oxadiazon | Azoxystrobin improved crabgrass control from pendimethalin by 15% to 20% but did not improve control from prodiamine and oxadiazon. | Ferrell et al. (2003) |
| Crabgrass, smooth | Kentucky bluegrass (*Poa pratensis*) | Interseeding with perennial ryegrass | Organic and conventional herbicide programs | Seeding reduced crabgrass infestations in organic programs but not the conventional program. The conventional program was extremely effective alone. | Miller and Henderson (2012) |

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| Dandelion (*Taraxacum officinale*) | Cool-season turf mixture | Interseeding | Biological herbicide *Sclerotinia minor* | Seeding + *S. minor* reduced dandelion to 2% to 6% cover compared with 33% to 39% for *S. minor* alone. Interseeding alone had no effect. | Abu-Dieyeh and Watson (2007b) |
| Dallisgrass (*Paspalum dilatatum*) | Common bermudagrass | Vertical mowing | Postemergence herbicides | Vertical mowing 30 min prior to herbicide application improved dallisgrass control. | Brown et al. (2022) |
| Dallisgrass | Tall fescue | Fall interseeding | Postemergence herbicide fluazifop | Interseeding improved control from herbicide by 20% to 25%. | Elmore et al. (2013b) |
| False-green kyllinga (*Kyllinga gracillima*) | Tall fescue | Fall interseeding | Postemergence selective herbicides | Interseeding or herbicides alone resulted in <50% control. Herbicides + interseeding resulted in 90% to 98% control. | Elmore and Tuck (2022) |
| Ground ivy (*Glechoma hederacea*) | Kentucky bluegrass | Three mowing timings relative to herbicide application | Five postemergence selective herbicides | The timing of lawn mowing did not alter herbicide efficacy. | Beck et al. (2014) |
| Silvery thread moss (*Bryum argenteum*) | Creeping bentgrass | Hollow-tine cultivation and vertislicing | Carfentrazone herbicide | Hollow-tine cultivation and vertislicing slightly reduced moss cover, even in the absence of carfentrazone. | Raudenbush and Keeley (2017) |
| Silvery thread moss | Creeping bentgrass | Topdressing and N fertilizer | Carfentrazone herbicide | Carfentrazone followed by four biweekly applications of sand topdressing or 12 kg N•$ha^{-1}$ controlled moss more than any practice alone. | Borst et al. (2010) |

herbicide programs for dallisgrass and false-green kyllinga were similarly improved when tall fescue interseeding occurred following postemergence herbicide applications (Elmore et al., 2013b; Elmore and Tuck, 2022). These studies conducted seeding 1–4 weeks after herbicide programs concluded (based on herbicide label restrictions), but this may not be widely practical. Future research could evaluate whether seeding and herbicide applications can be effective if conducted at different times of year. These interseeding studies broadly suggest that combining herbicides with practices to enhance turfgrass vigor (e.g. N fertilizer and fungicide applications) is important to improve herbicide efficacy against perennial weeds, but this topic deserves more research.

While most research evaluating integrated strategies focused on weeds that cannot be controlled with herbicides alone, many weeds such as crabgrass can be controlled by high rates of preemergence herbicides alone and minimal regard for cultural management. But there may be potential to use lower herbicide rates if nonchemical management is integrated. Research evaluating various mowing regimens and heights found that a low rate of prodiamine (0.34 kg $ha^{-1}$) was less effective at the lowest mowing height of 1.3 cm than higher mowing heights, and this was not explained by a decrease in turfgrass density (Cropper et al., 2017). Other work in bermudagrass found that maximum labeled rates of several preemergence herbicides were more effective at a 3.8 cm mowing height compared to a 1.5 cm mowing height in 1 year, but there was no effect of mowing height the other year (Gannon et al., 2015). A better understanding of how to reduce herbicide rates or application frequency in combination with nonchemical approaches is needed. Could lower preemergence herbicide rates provide season-long crabgrass control if used in conjunction with an allelopathic cultivar or a 'right-plant right-place' approach? What is the potential to reduce herbicide rates for tall fescue treated to prevent brown patch disease? Ferrell et al. (2003) found that the preemergence herbicide pendimethalin controlled crabgrass more when tall fescue competitiveness was enhanced by azoxystrobin for brown patch disease control. Brosnan and Breeden (2013) attributed the aforementioned bermudagrass control enhanced by tall fescue interseeding partially to fungicide applications to prevent brown patch disease.

Future research projects designed to examine integrated management practices should include herbicide or plant growth regulator rates that do not completely control the weed on their own to avoid muting the effect of the nonchemical practice (Diehl et al., 2021). This would help practitioners rank the efficacy of various treatment combinations, better assess the value of nonchemical practices, and apply the knowledge to a wide range of scenarios they encounter in the field.

## 4 Barriers to integrated weed management among practitioners and how to address them

Herbicide restrictions are increasing worldwide. Legislation severely restricts herbicide options in many countries of Europe and the UK (Hahn et al., 2020). In the USA, restrictions are limited but increasing. An ideal situation would be a transition to a system that decreases herbicide use and increases other management techniques without forced legislation. However, integrated pest management is a >50-year-old concept with limited adoption to date (Stern et al., 1959). There are several barriers to the adoption of integrated weed management that are specific to the turfgrass industry (Ervin et al., 2022) and others that are common to other crops (Nowak et al., 1996). In each case, both the complexity of biological systems and the uniqueness of human individuals prevent greater adoption.

More research is needed to improve agronomic tools, methods, and strategies for integrated weed management. Harker and O'Donovan (2013) point out that the research on integrated weed management has increased in recent years, but most of the knowledge base is still focused on the use of herbicides. If integrated weed management is to increase, the research funding into biological, physical, cultural, and organic control options must also increase to provide a pathway to sustainability. A recent example of funding toward the development of integrated solutions is the project 'Research and Extension to Address Herbicide-Resistance Epidemic in Annual Bluegrass in Managed Turf Systems', funded by the USDA National Institute of Food and Agriculture Specialty Crops Research Initiative program (award no.: 2018-51181-28436) (http://resistpoa.org). Programs and projects like this must increase in the future if sustainable weed management is to be increased in turfgrass ecosystems.

Scientists and educators need to increase and improve relationships with community partners to both better meet their needs and collaborate to develop solutions (Gavazzi and Gee, 2018). Ervin et al. (2022) noted that universities play a key role in bringing together turf professionals for both formal and informal information sharing. Turf practitioners recognize university scientists as trusted information sources (Ervin et al., 2022), but the high cost of obtaining the information may prevent their adoption (Nowak et al., 1996). Practitioners may not always be able to afford to attend local or regional conferences and workshops in lieu of their already busy work schedule.

The challenges related to employee turnover and finding skilled, knowledgeable labor make the adoption of integrated weed management techniques difficult. The turf industry as well as the nursery and landscape industry is known to have high employee turnover (Mathers et al., 2010; Patton and Reicher, 2011). While new employees entering the workforce are trained on the safe use of pesticides prior to becoming a pesticide applicator, their supervisor is often the only staff member with training on integrated weed management. Businesses that invest in training new and experienced employees may reduce turnover and be better able to utilize integrated weed management. One example of this is a >69 ha Science, Employee Education, and Development campus being built by The Davey Tree Expert Company (Kent, OH, USA) to train and retain employees (https://www.davey.com/about/seed-campus).

Additionally, more information sharing is needed in the turf industry for non-English-speaking people or those who speak English as a second language (Ervin et al., 2022; Patton et al., 2013b). Reaching those that need training can be a challenge, although programs designed for entry-level workers in the turf industry are rated highly, with 95% of attendees feeling better equipped to do their jobs and 72% feeling better able to save money for their employer (Patton and Reicher, 2011). In 2022, The University of Florida (Gainesville, FL, USA) hosted a field day tour entirely in Spanish to improve information accessibility (https://tinyurl.com/y4c92mmc).

For the investment in these employee training efforts to be fully realized, it will be critical to find new ways to involve homeowners (mowing and irrigation) and landscape managers/contractors (mowing, irrigation, and planting decisions) in the management of the lawn to integrate their practices (Ervin et al., 2022). For example, yellow nutsedge is known to be more competitive in over-irrigated soils (Ransom et al., 2009). Lawn care operators trained to identify an overwatering or similar issue need to share this issue with the homeowner or person who controls the irrigation system.

Another challenge to integrated weed management related to training is the complexity of the system. While killing a weed may seem like a simple proposition, integrated weed management is more complex than choosing an herbicide and spraying a weed. Each weed responds differently to cultural, biological, physical, and chemical control tactics. Practitioners need to understand those many factors for each of the common weed species they encounter to then develop an effective integrated control strategy. For example, to control annual bluegrass in a golf course putting green, a practitioner must understand the influence of N, P, and Fe applications on both annual bluegrass and the desirable putting green species, the influence of mowing height and grass clippings collection on species dynamics, the influence of soil pH and root zone moisture on plant growth and development, the management of soil compaction and soil dynamics of weed seed recruitment from the seedbank, the effectiveness of interseeding techniques, timings, and choice to increase plant competition, the influence of shade/light management on turfgrass and weed species dynamics, the potential interactions between plant pathogens and insect pests on the population dynamics between the weed and the desirable turfgrass species, the influence of plant growth regulators with three differing plant physiological sites of action, and lastly the effectiveness of preemergence and postemergence herbicides from differing modes of action, and the subsequent government regulations surrounding their use on golf course putting greens. It is a challenge just to know this information, let alone to synthesize it into an effective weed management program specific to each practitioner's site, labor budget, and equipment and chemical inventory. Decision support tools that provide guidance on integrated solutions (e.g. chemical and cultural) can reduce the complexity of the system. Readily accessible tools for turfgrass weed management include the Purdue Turf Doctor App (https://www.entm.purdue.edu/turfdoctor), Wisconsin Turf Pest Control Tool (https://turfpests.wisc.edu), and University of Tennessee Mobile Weed Manual (https://www.mobileweedmanual.com/home). However, these only address basic needs such as herbicide selection and weed identification and do not provide information on how to integrate nonchemical practices or optimize herbicide efficacy. The 'Turfgrass Weed Control for Professionals' guide (Patton et al., 2022) discusses strategies to optimize herbicide efficacy but does not cover integrated weed management. Other tools such as the Michigan State University GDD Tracker (https://gddtracker.msu.edu) and Cornell University Fore Cast (http://turf.eas.cornell.edu) also help turfgrass managers optimize application timing for certain herbicides but do not address nonchemical techniques. Innovative, comprehensive, and accessible resources for turfgrass managers are needed but who will fund the development and maintenance of these resources?

Locally adapted information is important. Turf management and the challenging weed species found in turf are heterogeneous in each region and within each state. As such, there is no one-size-fits-all approach. Ervin et al. (2022) advocate for local efforts to improve integrated weed management, as regional and national policies and practices are likely to fail. Weed management guides certainly should be authored at the national and regional levels by scientists, specialists, and educators, but recommendations need to be locally adapted to provide the best possible information. Information that is from a neighboring state or from across the country may be viewed as irrelevant by stakeholders (Nowak et al., 1996). The ShortCUTT newsletter (https://turf.cals.cornell.edu/news/shortcutt-newsletter) released weekly during the growing season by Cornell University (Ithaca, NY, USA) is a great example of a local and timely resource to help turfgrass managers integrate nonchemical strategies. These local resources also require funding from university agricultural experiment stations, grants and other funding programs, and other noncommercial interests.

Another barrier to increased adoption of integrated practices is related to information sharing and organization schemes (Ervin et al., 2022). In some segments of the turf industry such as golf courses or athletic fields, the turf manager or superintendent has almost complete control of the management system. The supervisor works with their staff to control aspects of mowing, irrigation, fertilization, and traffic management and all aspects of pest management using physical, biological, and pesticide control strategies in addition to turfgrass species and cultivar selection and site preparation when planting new swards. Whereas in the professional lawn care industry, the homeowner or a separate landscape maintenance contractor often controls the initial turfgrass species and cultivar selection at establishment and the subsequent mowing, irrigation, and traffic management. The professional lawn care operator (LCO) only governs the fertilizer and pesticide applications. The mowing contractor may be inadvertently responsible for spreading weeds from one lawn to another (Ervin et al., 2022) or weeds may encroach from the neighboring properties. The lack of control of all the cultural management practices undermines the LCO ability to develop and implement a sustainable approach to lawn weed management (Ervin et al., 2022).

Cost is another important barrier to integrated weed management. Practitioners may be willing but unable to adopt integrated weed management strategies because of the economic expense (Nowak et al., 1996). Herbicides are the primary pesticide used in turf on an acreage basis (Clark and Kenna, 2010) because of their affordability. Compared to physical removal of weeds by laborers, the total cost (e.g. labor, herbicide, fuel, and equipment) of an herbicide application is much lower. If herbicides are affordable, safe, and effective, what is the incentive to adopt a new weed management technique? Additionally, there is a high labor cost associated with pest monitoring (Clark and Kenna, 2010). Often, the highly trained staff with higher salaries are entrusted with scouting to properly identify the pest and its growth stage. Researchers are also guilty of developing integrated pest management techniques without considering the economic feasibility of these recommendations on practitioners. Scientists and extension/outreach specialists need to better document the environmental and economic benefits of a holistic, long-term integrated pest management system in a real-world scenario, although a recent example of this is the work of Rossi and Grant (2009). Integrated weed management is perceived as more expensive, so research and extension/outreach efforts need to document the return on investment in both the short and long term (Moss, 2019). A return on investment could be aided by better understanding consumer preferences for weed management, similar to what has been done to understand consumer preferences for turfgrass attributes (Ghimire et al., 2019; Hugie et al., 2012; Yue et al., 2012), how these attributes influence adoption (Yue et al., 2021), and how integrated weed management can be facilitated by the turfgrass manager (Barnes et al., 2018). What premium would consumers pay for a lawn care service that reduces pesticide use through integrated weed management? Financial incentives for turfgrass, similar to the US EPA Pesticide Environmental

Stewardship Program Grants for the agricultural community could also hasten the adoption of integrated weed management strategies.

Another barrier to the adoption of integrated weed management techniques is an unwillingness to adopt (Nowak et al., 1996). This unwillingness could be for several reasons. The high cost of investment in new equipment, such as a GPS/GIS sprayer, may prevent practitioner adoption of this technology as part of an integrated strategy to control pests. High costs of water or fuel may prevent the proper mowing (e.g. frequency) or irrigation of a lawn. Integrated weed management practices also carry with them an increased risk (real or perceived) of a negative outcome (Nowak et al., 1996). Consumers (e.g. golfers, homeowners, and property managers) have a high expectation for a near perfect, esthetically beautiful turf product (Clark and Kenna, 2010) and practitioners may be unwilling to try new practices due to uncertainty and risk associated with the outcome (e.g. too many weeds) and the subsequent impact on their income and employment.

A final barrier to the adoption of integrated weed management techniques relates to legislation, regulation, and litigation to remove herbicides from the list of approaches available. Those drafting legislation often do not appreciate the complexity of the problem. They may assume that citizens have access to effective, alternative solutions when imposing herbicide restrictions and enact legislation without a careful study of alternatives to the products banned. In some cases, the alternatives proposed may have a higher safety risk to the applicator despite the perceived benefit to the environment that might accompany a change. For example, fearing potential litigation or human safety related to glyphosate use, businesses and municipalities banned the use of glyphosate and switched to the use of vinegar (containing acetic acid) as an alternative organic herbicide. These decisions were made without a careful review of the safety of the alternative product to applicators or its effectiveness to control weeds. Acetic acid herbicide solutions work as contact herbicides, offering short-term weed control, but they are known to burn skin and cause serious-to-severe eye injury, including blindness (Webber et al., 2018). In comparison, glyphosate is a systemic herbicide better able to kill weeds than acetic acid (Domenghini, 2020) without risk to the applicator (Kougias et al., 2021), and without risk of developing any form of cancer, including non-Hodgkin's lymphoma (Andreotti et al., 2018). Regulation of existing technology (e.g. herbicides) without careful study and funding to develop alternatives will limit the availability and access to the strategies (e.g. tools) that practitioners need to implement integrated weed management.

## 5 Conclusion and future trends

Weeds are major pests that reduce esthetics and functionality of turfgrass ecosystems. Knowledge required for effective and sustainable turfgrass weed management has evolved in recent years as weeds develop resistance to herbicides, government restriction of broad-spectrum herbicides has increased, and registration of new herbicide active ingredients has slowed. This chapter provided an in-depth discussion on relevant and recent developments in synthetic herbicides, alternatives to synthetic herbicides, and nonchemical strategies for integrated and sustainable turfgrass weed management, including cultural, physical, and genetic approaches. Advances in integrated turfgrass weed management strategies and barriers preventing adoption of those strategies were also presented in this chapter. Finally, this chapter also presented opportunities for research and development to improve an overall integrated and sustainable approach to turfgrass weed management.

## 6 Where to look for further information

Agronomy Monograph 56 titled *Turfgrass: Biology, Use, and Management*, edited by John Stier, Brian Horgan and Stacy Bonos contains chapters on both integrated pest management and weed management in turfgrass. (Stier, J. C., Horgan, B. P. and Bonos, S. A. (2013). *Turfgrass: Biology Use and Management. Agronomy monograph 56*. Madison, WI: Crop Sci Soc of America, 1307 p).

Current websites specific to various centers of research include the following:

- Resources from a collaboration of 16 university scientists funded by the USDA to limit the impact of annual bluegrass in turfgrass (Resistpoa.org).
- Annual research reports from the Rutgers Center for Turfgrass Science (https://turf.rutgers.edu/research/reports/).
- Resources for turfgrass practitioners from the University of Tennessee Turfgrass Weed Science Program (https://www.tnturfgrassweeds.org/resources).
- Resources for turfgrass practitioners from the Purdue University Turfgrass Program (https://turf.purdue.edu/turfgrass-weeds/).
- Resources for turfgrass practitioners from the North Carolina State University Turfgrass Program (https://www.turffiles.ncsu.edu/grasses/).
- Extension guidebook. *Turfgrass Weed Control for Professionals* from Purdue University (https://mdc.itap.purdue.edu/item.asp?Item_Number=TURF-100).

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