

# Managing cool-season turfgrass without herbicides: Optimizing maintenance practices to control weeds

Daniel Hahn<sup>1</sup>  | Rossana Sallenave<sup>2</sup>  | Cristina Pornaro<sup>3</sup> | Bernd Leinauer<sup>1</sup> 

<sup>1</sup> Department of Plant Sciences, Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands

<sup>2</sup> Department of Extension Animal Sciences and Natural Resources, New Mexico State University, Las Cruces, NM, USA

<sup>3</sup> Department of Agronomy, Food, Natural Resources, Animals, and Environment, University of Padova, Padova, ITALY

## Correspondence

Bernd Leinauer, Department of Plant Sciences, Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands.

Email: [bernd.leinauer@wur.nl](mailto:bernd.leinauer@wur.nl)

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## Abstract

Bans on the use of synthetic herbicides require innovative management approaches to maintain the attractiveness and usability of turfgrass swards. Such measures should include the use of locally adapted cultivars that germinate and establish quickly, resulting in the densest possible stands. Additionally, a number of turfgrasses have been reported to produce allelopathic substances that inhibit common turfgrass weeds. Mowing heights should be set to achieve maximum weed suppression while still providing acceptable quality for desired use. Sustainable turfgrass management programs have led to a reduction in fertilizer inputs; however, without the availability of herbicides, fertilization regimes need to be re-examined. The literature suggests that broadleaf weeds are reduced but never fully controlled when more N is applied; therefore, finding a balance between what is needed and what is environmentally safe and sustainable is critical. Organic herbicides include plant pathogens from the fungus *Phoma* and strains of the bacterium *Pseudomonas fluorescens*. Both can be used to control several weeds common to turfgrasses. Acetic acid has also been shown to have herbicidal activity; however, it has limited residual activity, and its efficacy remains questionable on mature weeds. Thermal weed control can be used to sterilize a seedbank or spot treat existing weeds. Future turfgrass breeding programs could focus on understanding and enhancing the allelopathic potential of turfgrasses to outcompete weeds more effectively. Furthermore, more research should be directed at assessing the competitiveness of certain turfgrasses against weeds within the limitations of producing turfgrass areas of acceptable aesthetics and playing quality.

## 1 | INTRODUCTION

Weeds are plants that are defined as undesirable in a specified area because of their ability to compete with native or desirable plant species (McCarty, Murphy, &

Turgeon, 1994). Turfgrasses compete with weeds for nutrients, water and space below ground (Snaydon, 1971), and for light above ground (Holt, 1995). Moreover, the presence of weed species in turfgrasses reduces playing quality, aesthetic value, and usability (Larsen, Kristoffersen, &

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Fischer, 2004; McCarty et al., 1994; McElroy & Martins, 2013; Stewart-Wade, Neumann, Collins, & Boland, 2002). Weed species rapidly germinate in exposed soil (McElroy & Martins, 2013) caused by abiotic factors, such as vehicular or human wear, drought, shade, cold, as well as by biotic factors affecting turfgrasses such as pest and disease damage (Brodie & Burton, 1967; Busey, Broschat, & Center, 1982; Waddington, T.R., J.M., & Moberg, 1978). Established weed species have a lower wear tolerance compared with turfgrasses, which increases the risk of soil exposure on weed infested turfgrass areas (McElroy & Martins, 2013). In terms of their aesthetic appearance, weeds often stand out because of enhanced floral production or color differences vs. turfgrass (McCarty et al., 1994). Additionally, some turfgrass weed species, such as dandelion (*Taraxacum officinale* F. H. Wigg) and white clover (*Trifolium repens* L.), are too close to the soil to be removed by mowing and produce patches that disrupt uniformity and affect ball roll and lie in sports scenarios (Larsen et al., 2004).

Turfgrass areas infested with weeds are often considered a sign of mismanagement (Masin, Zuin, Archer, Forcella, & Zanin, 2005); however, weeds can establish even under optimal management (Busey, 2003). Nevertheless, weeds establish opportunistically if managers fail to reduce overall weed densities to a minimum and maintain a dense turfgrass sward.

Herbicides are the predominant method to control weeds in turfgrass management particularly in large areas such as golf course fairways (Dahl-Jensen, Norman Petersen, & Aamlid, 2014). No new herbicide mechanism of action (MOA) has been discovered since the 1980s, and an ever-increasing risk of herbicidal resistance could lead to virtually complete resistance to all conventional mechanisms of action by 2050 (Westwood et al., 2018). In 2017, the Weed Science Society of America listed >300 commercially sold modes of action to control weeds in agriculture and turfgrass (Weed Science Society of America, 2017). The use of herbicides in the United States golf industry increased by an average of ~2% between 2007 and 2015 (Golf Course Superintendents Association of America, 2017) with regional differences; for example, golf courses located in transition zones increased herbicide use by 13% whereas north-central regions reduced use by 8% (Golf Course Superintendents Association of America, 2017).

In the European Union, much stricter bans on herbicides have been established. The risk of herbicide resistance (De Prado & Franco, 2004; Heap, 1997), health risks associated with herbicide exposure (Karabelas, Plakas, Solomou, Drossou, & Sarigiannis, 2009), and environmental concerns (Stoate et al., 2009) have led to a restriction of synthetic herbicide products (Barzman & Dachbrodt-Saaydeh, 2011). Today, only 123 herbicides are approved for commercial use (European Commission, 2017), and

strict bans have been introduced in the turfgrass sector. For example, in Germany, only two herbicides, namely Banvel M and Nasalt (active ingredients Dicamba and MCPA, respectively), can be used on golf courses (German Golf Association, 2017). In Great Britain, the maximum allowable overall load of herbicide active ingredients that may be applied to amenity turfgrass (public areas, residential lawns, sports field, golf courses, etc.) was reduced from 1837 t in 2006 to 671 t in 2012, a 64% reduction (Department for Environment, Food and Rural Affairs, 2015). Denmark has set maximum permitted levels of pesticide use for designated areas on golf courses (European Commission, 2017). This has resulted in an 82.7% decrease in annual pesticide use on golf courses from 1998 to 2014 (T. K. Petersen, personal communication, 2018). In Holland, the turfgrass industry has agreed to accept a complete ban of all pesticides by 2020 (Government of the Netherlands, 2017).

It is clear that the future of weed control in European turfgrass landscapes will be limited to nonchemical herbicide strategies. Few studies, other than those of Dahl-Jensen et al. (2014) and Silvertown et al. (2006), have investigated nonchemical management practices for weed suppression in amenity turfgrasses. In Scandinavia, most golf courses can cope with herbicide-free management but Dahl-Jensen et al. (2014) found that weed densities severely increased after a period of ~3 yr. Weed control is most effective under such circumstances when a variety of methods are used to support the growth of desirable species and reduce the fitness of unwanted weed species (Marble, Koeser, & Hasing, 2015).

Weeds are early colonizers and their persistence is dependent on their competitive ability against turfgrasses (Watschke, Dernoeden, & Shetlar, 1995). Nonchemical approaches to control weeds must therefore focus on reducing the availability of ecological niches in a turfgrass sward for weed colonization, germination, and establishment (Larsen et al., 2004). Maintaining dense turfgrass swards is primarily dependent on the genetic ability of turfgrasses to resist local abiotic and biotic stresses (Watschke & Engel, 1994). Secondly, maintenance practices aimed at promoting turfgrass growth favor the competitive ability of turfgrasses to outcompete weeds (Dahl-Jensen et al., 2014). The following sections provide a perspective on amenity turfgrass management approaches focused on weed control without the use of herbicides.

## 2 | TURFGRASS SELECTION

Cultivars that germinate and establish quickly should be selected in newly seeded areas to reduce the chances of weed germination. The selected cultivars need to be adapted to the local climate to provide the densest turfgrass

sward possible. Every year, the British Society of Plant Breeders (<https://www.bspb.co.uk/#>) Turfgrass Seed manual (British Society of Plant Breeders, 2020) and the National Turfgrass Evaluation Program (<https://www.ntep.org>) rank the majority of turfgrass cultivars for different characteristics such as visual merit, shoot density, live ground cover, resistance to abiotic and biotic stress, fineness of leaf, cleanness of cutting, disease resistance, color, and recovery. This allows turfgrass managers to select turfgrass cultivars that establish and become dense quickly for outcompeting weeds in seeded areas.

Selecting turfgrasses for resistance against local biotic (e.g. insects, diseases etc.) stresses can have a secondary effect on weed establishment over time (Busey, 2003). Davis (1958) recorded an outbreak of leaf blight [*Dreschlera poae* (Baudys) Shoemaker] in Kentucky bluegrass (*Poa pratensis* L.) that caused an outbreak of broadleaf weeds infestation. Waddington et al. (1978) attributed annual bluegrass (*Poa annua* L.) invasion in creeping bentgrass [*Agrostis stolonifera* L. var. *palustris* (Huds.) Farw.] swards to injury after dollar spot (*Sclerotinia homoeocarpa*) outbreaks. Brodie and Burton (1967) found a reduction in density of ‘Tifgreen’ [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] under nematodes (*Belonolaimus longicaudatus* Rau) infestation and increased establishment of spotted spurge [*Euphorbia maculata* L. [= *Chamaesyce maculata* (L.) Small]] (Brodie & Burton, 1967).

Besides biotic stresses, abiotic stresses (e.g. drought, infertility etc.) can also increase weed densities in turfgrass swards. Perennial ryegrass (*Lolium perenne* L.) showed susceptibility to colonization by spotted spurge under reduced irrigation (Gibeault, Meyer, & Youngner, 1985). In a trial for which ‘Big Horn’ blue fescue [*Festuca glauca* Vill. [= *F. ovina* var. *glauca* (Vill.) W. D. J. Koch]] and ‘Aurora’ hard fescue [*F. trachyphylla* (Hack.) R. P. Murray] were kept without fertilizer and irrigation, the turfgrasses showed superior resistance to smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] and white clover infestation vs. tall fescue (*Lolium arundinaceum* (Schreb.) S.J. Darbyshire) cultivars (Dernoeden, Carroll, & Krouse, 1994). The authors also found that tall fescue cultivars were poorer competitors against weeds under low cutting regimes vs. blue fescue and hard fescue.

Competitive growth studies between monocultures and cultivars in mixtures may provide insight into potential weed suppressing characteristics. In cool-season turfgrasses, a mixture of turfgrasses under low-maintenance regimes is generally more effective in controlling weeds than a single species sward (McKernan, Ross, & Tompkins, 2001). Mixtures of Kentucky bluegrass and perennial ryegrass achieved 8% higher leaf area index than monocultures of each single species, which may explain the supe-

rior weed suppression characteristics of such mixtures (Brede & Duich, 1984). Moreover, cultural management practices can be adjusted to favor certain species; however, dominance is a combination of the genotype and the environment. For example, long-leaved perennial ryegrass is dominant over short-leaved perennial ryegrass genotypes under infrequent cutting because long-leaved genotypes are better competitors for light (Hazard & Ghesquiere, 1995). Kentucky bluegrass can dominate over creeping red fescue (*F. rubra* L. subsp. *rubra*) at high levels of nitrogen (N) input, whereas creeping red fescue dominates at low levels of N (Juska, Tyson, & Harrison, 1955). At low temperatures, mixtures of red fescue [*Festuca rubra* L. subsp. *litoralis* (G. Mey.) Auquier] and perennial ryegrass are capable of germinating more quickly than other species, potentially increasing their competitive ability over weeds (Larsen & Bibby, 2005). In mixtures of creeping bentgrass, red fescue, and Kentucky bluegrass, the creeping bentgrass dominated when the turfgrass was maintained at close mowing heights (Davis, 1958).

A common approach in turfgrass management is to encourage the growth of turfgrasses requiring less inputs of valuable resources, which is critical for a sustainable management approach (Cisar, 2004). However, encouraging the use of low-input species is only one aspect of sustainability. The most sustainable turfgrass species are those that provide the best performance for desired use year-round as well as being adapted to local pest, disease, and weed problems.

### 3 | SEEDING AND OVERSEEDING STRATEGIES

The choice of a proper seeding rate as well as the use of overseeding to increase turfgrass densities can provide a competitive edge over weeds (Parr, 1985). The benefits of planting newly constructed areas with higher than recommended seeding rates to suppress weeds have been reported. For example, Beard, Martin, and Mercer (1980) showed that seeding Kentucky bluegrass at 90 kg ha<sup>-1</sup>, instead of 45 kg ha<sup>-1</sup>, reduced weed cover on average by 21% 2 mo after seeding.

Overseeding strategies can successfully reduce weed populations if sufficient seed germination is achieved (Aamlid, 1992; Begon, Harper, & Townshend, 1996; Larsen & Fischer, 2005; Larsen et al., 2004). Harris (2008) found that overseeding at seeding rates ranging between 12.5 g m<sup>-2</sup> and 100 g m<sup>-2</sup> all provided denser swards with fewer weeds than not overseeding if seeds successfully germinated. Overseeding can be integrated as a regular practice to increase the competitiveness of turfgrasses. Best practices to increase germination after overseeding

and reduced weed pressure include overseeding during reduced weed growth, providing good seed–soil contact, and following a fertilizer regime (Vargas & Turgeon, 2004). During germination, sufficient phosphorous (P) must be present, whereas after establishment, N is required to facilitate shoot and root growth (Christians, 2016; McVey, 1968).

Proper species selection for overseeding purposes is also crucial. Perennial ryegrass showed good germination rates regardless of whether or not water and fertilizer were applied (Dahl-Jensen, Bühler, Kvalbein, & Aamlid, 2017; Elford, Tardif, Robinson, & Lyons, 2008). Additionally, perennial ryegrass germinates quickly and has good root and shoot competition against weeds (Haugland & Froud-Williams, 1999). Quick and successful establishment is important to outcompete weed seedlings for light and fertilizer (Jeangros & Noesberger, 1990; Snaydon and Howe, 1986). Frequent overseeding with high rates of perennial ryegrass appears to provide competition against perennial weeds over the short term when weed cover is high and should be considered an important part of a weed management program for municipal turfgrass managers (Elford et al., 2008). Increasing overseeding rates in existing swards could be a long-term weed management strategy. The effect of overseeding might be especially noticeable on sparse turfgrass swards (Dahl-Jensen et al., 2014; Nyholt, 2010).

Another approach to aid turfgrass establishment in newly constructed and seeded areas is to use amendments. Products include Turfiber, alfalfa hay, oat straw, straw mulch, mat seeding, hydro mulch, and other materials. These products increase moisture retention in the soil and suppress weed germination (Barkley, Blaser, & Schmidt, 1965; Hansford, 1981; Hensler, Baldwin, & Goatley, 2001; Shearman, Steinegger, Kinbacher, & Riordan, 1979; Sowers & Welterlen, 1988). Emphasis must be placed on increasing germination success after overseeding using adequate machinery to place seeds at the right soil depth, provide uniform irrigation coverage, and provide adequate fertilization.

#### 4 | ALLELOPATHIC POTENTIAL

The biological phenomenon of allelopathy has been effectively used in agriculture by producers to suppress weeds (Jabran, Mahajan, Sardana, & Chauhan, 2015). The capacity of turfgrasses to produce allelopathic substances that influence weed invasion has been reported for a variety of turfgrasses. Turfgrass roots are capable of preventing root invasion from competitor plants by producing leachates that can modify the soil matrix or lead to toxicity after absorption by competitor plants (Seigler, 2006). Thus, allelopathy can be described as a competition mech-

anism that could provide some control of weed species in turfgrass areas.

The application of aqueous leachates derived from perennial ryegrass, red fescue, and Kentucky bluegrass to rooted cuttings of forsythia (*Forsythia ×intermedia* Zabel) reduced top growth of this woody plant (Fales & Wakefield, 1981). Perennial ryegrass showed allelopathic potential on clover, which was enhanced by crown rust (*Puccinia coronata* Corda f. sp. *lolii* Brown) infection of perennial ryegrass (Mattner & Parbery, 2001). Understanding the mechanisms of such interactions could lead to their improved effectiveness in the field and to the isolation of allelopathic compounds for biological herbicide formulations.

Peters and Luu (1985) observed tall fescue pastures free of other plant species and attributed the absence of other plants to the allelopathic potential of tall fescue. In bioassay trials, tall fescue exudates reduced seedling growth of rape (*Brassica napus* L.), birdsfoot trefoil (*Lotus corniculatus* L.), red clover (*Trifolium pratense* L.), and several other common turfgrass weeds (Luu, Matches, & Peters, 1982; Peters & Zam, 1981; Rice, 1987). Clippings of creeping red fescue and colonial bentgrass (*Agrostis capillaris* L., [= *Agrostis tenuis* Sibth.]) reduced germination and early growth of white clover in container studies conducted by Norrington-Davies and Buckeridge (1994). Bertin, Senesac, Rossi, DiTommaso, and Weston (2009) showed that weed suppression varied greatly among fescue cultivars. They found strong creeping red fescue cultivars and Chewings fescue cultivars to be most effective at weed suppression.

Allelopathy based breeding programs could be developed to select for allelopathic turfgrass varieties. A future approach might be to develop biological plant protection products from phytotoxic exudates. Putative compounds could be isolated from a methanol extract of root material, and the chemical structure could be determined by high-resolution mass spectrometry, infrared spectroscopy, and hydrogen-1 nuclear magnetic resonance (Kato-Noguchi, 2003). Once allelopathic cultivars or species demonstrating strong competitiveness against weeds are identified, turfgrass managers should consider establishing these species over time.

#### 5 | ADJUSTING MOWING PRACTICES AND FERTILIZATION TO INCREASE COMPETITIVENESS OF TURFGRASS SPECIES

Mowing heights should be adjusted to a point where the turfgrass canopy becomes dense enough to suppress weed populations and short enough to provide good playing conditions. Cutting heights of turfgrasses can be adjusted throughout the year to stimulate either above- or

belowground growth. The same applies to fertilization applications. Fertilization can lead to quick or slow growth depending on the type of fertilizer being used. Fertilization can encourage above- or belowground growth, depending on the application method, timing, and type of fertilizer. Practices such as aeration can generally increase infiltration rates, rooting depth, and turfgrass health.

## 5.1 | Mowing practices

Increasing mowing frequency of turfgrasses results in less root mass, rhizome, and stolon production but increased shoot density (Hull, 2000). The effect of mowing height on turfgrass weeds, such as crabgrass (*Digitaria* spp.), is well documented (Busey, 2003). Raising cutting heights has been found to reduce crabgrass densities over time in Chewings fescue (*F. rubra* spp.) (Jagschitz & Ebdon, 1985), Kentucky bluegrass (Dunn, Nelson, & Winfrey, 1981; Niehaus, 1974), tall fescue (Dernoeden, Carroll, & Krouse, 1993; Hall, 1980; Voigt, Fermanian, & Haley, 2001), and fine fescue species (Dernoeden, Fidanza, & Krouse, 1998). Using variable mowing heights throughout the season had no effect on controlling crabgrass in tall fescue (Cropper, Munshaw, & Barrett, 2017). Therefore, using a consistently high mowing height might be most effective to increase competitiveness of turfgrasses against crabgrass.

Adams (1980) showed that annual bluegrass cover, in a perennial ryegrass dominated sward, decreased from 34 to 9% when the cutting height was raised from 1.25 to 7.5 cm. However, few studies exist that have investigated the relationship between mowing height and broadleaf weed densities. Fine fescue was reported to be more competitive over a mixture of broadleaf weeds (e.g. dandelion, white clover, crabgrass) when the mowing height was raised from 1.9 to 5.1 cm (Davis, 1958). Gray and Call (1993) found that raising the mowing height to 6 cm in tall fescue dominated turfgrass was successful in reducing common blue violet (*Viola sororia* Willd).

Studies suggest that weed densities can generally be reduced but never fully controlled with only mowing and fertilization (Busey, 2003). The extent to which overall weed densities can be lowered is also dependent on the competitive ability of the turfgrass species composition. In a trial with different mowing heights, fertilizer rates, and turfgrass species, DeBels, Griffith, Kreuser, Melby, and Soldat (2012) found 'Kenblue' Kentucky bluegrass had the highest weed encroachment regardless of fertilizer or mowing treatment.

Raising cutting heights usually increases competitiveness of desirable turfgrasses; however, it is unclear if small changes within the limitations of usability has an effect on weed pressure. For example, golf fairways are usually

maintained at heights ranging from 8 to 25 mm, but there are no studies that have examined whether a high over a low cutting height provides superior weed control. Common sense suggests that turfgrass should be kept as dense as possible throughout the year, hence, cutting heights should be increased if turfgrass is sparse but can be lowered if turfgrass remains sufficiently dense. Furthermore, mowing height and frequency are dependent on the growth rate of the turfgrass. Factors that influence growth rates include genotype, climate, the growth medium, and the management input of water and fertilizer. Therefore, it seems unlikely that weed pressure will be reduced by small changes in cutting height alone.

## 5.2 | Handling of clippings

Returning clippings to turfgrasses is thought to increase soil levels of carbon and N if microbial activity is sufficient to mineralize N (Haley, Wehner, Fermanian, & Turgeon, 1985; Law, Trappe, Jiang, Turco, & Patton, 2017; Macdonald, Powlson, Poulton, & Jenkinson, 1989; Qian et al., 2003; Shepherd, Stockdale, Powlson, & Jarvis, 1996; Starr & DeRoo, 1981). Knot et al. (2017) and Qian et al. (2003) applied the century model and calculated that returning clippings can reduce a turfgrasses N requirement by 25% if it is 1–10 yr old, by 33% if it is 11–25 yr old, and >50% if it is older than 25 yr. However, since additional nutrients can also be provided by increasing fertilizer rates, the decision to remove clippings is based more on aesthetic or financial considerations. The positive effects of returning nutrients derived from clippings to the system can be offset by the addition of weed seeds (Heckman, Liu, Hill, DeMilia, & Anastasia, 2000). Weed-related negative effects of returning clippings have been especially observed with annual weeds, which survive by producing large numbers of seeds. Clipping removal led to a 60% reduction of viable annual bluegrass seeds in a bentgrass dominated turfgrass sward (Gaussoin & Branham, 1989). Therefore, if the turfgrass sward is dominated by unwanted annual bluegrass, clippings removal should be considered to reduce the seedbank build up.

In contrast, clippings can contain allelochemical compounds, which have herbicidal activity (Akbari, Sajedi, Gomarian, & Akbari, 2015). Bertin, Yang, and Weston (2003) and Wu, Harivandi, and Guo (2002) conducted studies in which these compounds were isolated and tested in pot and petri dish experiments. Allelopathic compounds isolated from a mixture of perennial ryegrass, Kentucky bluegrass, and particularly red fescue inhibited germination and seedling growth of prostrate pigweed (*Amaranthus blitoides* S. Watson) (Akbari et al., 2015). It is unclear if simply returning clippings after mowing has

an allelopathic-based inhibitory effect on weeds, as allelopathic compounds interact with soil physical and chemical parameters, climate, and other biotic factors such as microbial activity (Wu et al., 2002), all of which can influence allelopathic efficacy.

### 5.3 | Fertilization

Fertilization changes botanical composition and reduces species richness through competitive exclusion but increases biomass in plant communities (DiTommaso & Aarssen, 1989; Gough, Osenberg, Gross, & Collins, 2000; Grime, 1973; Templeton & Taylor, 1966). For example, tees, fairways, and greens are ideally dominated by only a few desirable turfgrass species to produce high quality surfaces (Bridges, 1994). Consequently, fertilization is a powerful tool to encourage dominance of desirable turfgrass species. In the absence of herbicides, turfgrass managers may need to re-examine some traditional cultural practices that have fallen out of favor in recent times because of budget constraints and environmental concerns. In particular, increased fertilization rates that have been shown to provide competitive edges to turfgrasses over weeds are now discouraged because of fertilizer costs, risk of groundwater leaching of nitrate, as well as surface runoff of excess fertilizer into receiving water bodies that lead to algal blooms among other things.

Nitrogen is the most limiting nutrient for plant growth (Bowman, Theodose, Schardt, & Conant, 1993). In aerated soils, plants acquire N mainly through inorganic forms of nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ). Availability of N is subject to biotic and abiotic processes affecting the total pool of soil N. Minor portions of N are utilized in organic forms, that is, amines and amino acids (Devienne-Barret, Justes, Mchet, & Mary, 2000; Lipson, Raab, Schmidt, & Monson, 2001). Application of N to grassland systems changes the competitive ability of turfgrasses against weeds (Silvertown, 1987; Silvertown et al., 2006). Calhoun, Rinehart, Hathaway, and Buhler (2005) reported that applying N to a mixture of Kentucky bluegrass, perennial ryegrass, and red fescue at a rate of  $150 \text{ kg ha}^{-1} \text{ yr}^{-1}$  reduced white clover density by 61–88% in a 4-yr study period. White clover was significantly reduced in tall fescue pastures when  $135 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  was applied (Rajaniemi, 2002). A turfgrass sward dominated by Kentucky bluegrass maintained with  $196 \text{ kg ha}^{-1} \text{ yr}^{-1}$  of N exhibited better visual turfgrass quality with lower weed densities than plots receiving no fertilizer (DeBels et al., 2012). Studies of Kentucky bluegrass, tall fescue, and Chewings fescue turfgrass swards showed that higher rates of N fertilizer reduced crabgrass densities significantly but did not result in full weed control (Dernoeden

et al., 1993; Dunn et al., 1981; Jagschitz & Ebdon, 1985; Johnson, 1981; Johnson & Bowyer, 1982; Murray, Klingman, Nash, & Woolson, 1983; Voigt et al., 2001). Johnson and Bowyer (1982) reported that Kentucky bluegrass plots receiving  $300$  and  $600 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  had lower dandelion densities ( $\sim 30$  and  $<10\%$ , respectively) than plots that were not fertilized (40% dandelions). Other studies in which broadleaf weed composition was not given reported minimal weed densities when  $300 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  was applied to Kentucky bluegrass- or tall fescue-dominated turfgrass swards (Haley et al., 1985; Voigt et al., 2001). The literature suggests that broadleaf weeds are reduced when more N is applied, therefore, finding a balance between what is needed and what is environmentally safe and sustainable is critical.

Established turfgrass that is not over irrigated loses on average  $<5\%$  of the N applied when rates of  $200$ – $300 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  are used (Barton & Colmer, 2006). Therefore, maintaining annual application rates of total N to turfgrass below the upper threshold of  $300 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  could be recommended. Such a high rate of N is rarely applied to any turfgrass area, hence, if sensible turfgrass management approaches are used, such as frequent, low doses of N, the risk of environmental pollution of surface and groundwater is minimized, and the benefits of outcompeting weeds are maximized.

Unfortunately, N fertilization has also been shown to increase production of annual bluegrass, which outcompetes desirable turfgrass species (Dest & Guillard, 1987; Lodge & Lawson, 1993). Such a transition is a concern for turfgrass managers. Nam-Il, Ogsasawara, Yoneyama, and Takeuchi (2001) reported that annual bluegrass only requires  $300 \text{ mg kg}^{-1} \text{ N}$  compared with bentgrass ( $1000 \text{ mg kg}^{-1} \text{ N}$ ) to produce maximum shoot and root growth in a greenhouse study. Growth of both species, particularly root growth, is very responsive to N and to a lesser extent to P and potassium (K) levels (Nam-Il et al., 2001). However, the competitive advantage of annual bluegrass over other turfgrass species in N fertilizer trials is not conclusive. A minimal increase of 12–17% in annual bluegrass cover was observed in perennial ryegrass dominated turfgrass when N rates were increased from 0 to  $352 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  (Adams, 1980). Gaussoin and Branham (1989) observed an increase in annual bluegrass cover in 1 yr out of three when  $293 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  was applied to a mixture of annual bluegrass and creeping bentgrass instead of  $98 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ . In contrast, Calvache et al. (2017) reported that changing N or P fertilizer rates had no effect on annual bluegrass densities in bentgrass- and fescue-dominated golf greens. The effect of N rates on the competitive ability of annual bluegrass might differ because of differences in soil type, category of fertilizer, method of application, or soil pH. For example, in a bentgrass and annual bluegrass mixture,

foliar application of N favors annual bluegrass growth, whereas granular applications increase bentgrass growth (O'Connor, Hébert, Powers, Jordan, & Lyons, 2018). Moreover, Lodge and Lawson (1993) reported that a stepwise increase in pH from 4.5 to 5.5, through the application of lime for 1 yr, considerably increased annual bluegrass cover from 0 to 30% in a fescue–bentgrass dominated golf green.

For turfgrass managers, it is often difficult to estimate minimum levels of N required to provide a turfgrass with a competitive edge over weeds. The approach used by agricultural producers could be followed in such cases. The critical N amount in agriculture is defined as the minimum concentration needed to achieve maximum plant growth. As plants mature, critical N concentrations decrease (Gastal & Lemaire, 2002). Turfgrass managers should focus on limiting N applications to minimum amounts needed to produce an acceptable level of playing quality or aesthetic appeal. Acceptable playing quality or aesthetic appeal can be measured objectively or defined by a combination of factors such as human expectations, budget limitations, and ecological considerations.

As the addition of N influences the competitive ability of turfgrasses over weeds, the dose and type of other nutrients added to a turfgrass area also influence turfgrass species composition. In a long-term parkland study, legumes established better in plots fertilized with P and K (>30% of ground cover), while turfgrasses dominated in plots fertilized with N (~90% of ground cover) (Silvertown, 1987; Silvertown et al., 2006). Phosphorous and K fertilizer applied consistently at high rates favored annual bluegrass invasion into bentgrass swards (Goss, Brauen, & Orton, 1975; Kuo, 1993a; Waddington et al., 1978). In low-P soils that are acidic, bentgrass was found to outcompete annual bluegrass because it was more efficient at absorbing P under those conditions (Kuo, Brauen, & Jelium, 1992). Consequently, macronutrients, such as P and K, should only be applied if soil levels are low because annual bluegrass and broadleaf weeds such as dandelion are better competitors when soil levels of these minerals are high.

Other strategies to outcompete annual bluegrass include the application of sulfur to acidify the soil and the reduction of N applications (Dest & Guillard, 1987; Goss et al., 1975). High levels of sulfur (168 kg S ha<sup>-1</sup> yr<sup>-1</sup>) lowered the pH of the soil, which in turn reduced P availability and annual bluegrass densities in creeping bentgrass swards (Goss, 1974). Broadleaf weeds become somewhat less competitive when soil pH is lowered; this could potentially be achieved by the application of iron. Also, lowering the soil pH with long-term applications of ammonium sulfate led to reduced broadleaf weed populations and in some cases to weed-free turfgrass (Escrit & Lidgate, 1964; Thompson, Clarke, & Heckman, 1995). In acidic soils, the application of calcium favors bentgrass growth over annual bluegrass

(Kuo, 1993b). Furthermore, applying 1.68 kg ha<sup>-1</sup> yr<sup>-1</sup> of both iron and magnesium to bentgrass has been shown to suppress annual bluegrass by 65% (Bell, Odorizzi, & Danneberger, 1999); however, the pH must be maintained at an optimum level for turfgrass growth to maintain competitiveness.

Fertilization may not only affect growth of desired turfgrasses but can also benefit broadleaf weeds in a stand. Dodd, Silvertown, McConway, Potts, and Crawley (1994) and Tilman, Tilman, Crawley, and Johnston (1999) documented that dandelion growth responded positively to K fertilization and increased 17- to 20-fold vs. nonfertilized controls in a mesotrophic grassland.

The timing of fertilizer applications is crucial to increase the ability of turfgrasses to outcompete weeds. For example, Kentucky bluegrass fertilized in spring and fall had significantly lower crabgrass densities than when fertilized in fall or summer (Dunn et al., 1981). Tall fescue fertilized in fall with two split applications each of 73 kg N ha<sup>-1</sup> was more competitive against weeds than a single spring application of 73 kg N ha<sup>-1</sup> (Hall, 1980). Fertilizer aids turfgrass growth and competitiveness but neither fall nor spring fertilization had an effect on crabgrass germination levels (Turner & van Acker, 2014).

Placement of fertilizer may also be important in weed suppression. The application of fertilizer close to the roots has been shown to suppress weed growth in agronomic studies (Chauhan & Ahugbo, 2013; Kirkland & Beckie, 1998; Mashingaidze et al., 2010). This weed suppressing effect of fertilizer placement has not been observed in landscape planting systems because of the ample availability of nutrients in the soil (Marble et al., 2015) but might have implications for turfgrass areas that are constructed on sand-based soil.

## 6 | BIOHERBICIDES

### 6.1 | Fungi based herbicides

*Phoma herbarum* is a fungal plant pathogen that causes leaf spot on a wide range of host plants (Gilardi, Matic, Gullino, & Garibaldi, 2017). The fungus produces the toxic metabolite 3-nitro-1,2-benzenedicarboxylic acid (3-nitrophthalic acid), which has herbicidal activity (Vikrant, Verma, Rajak, & Pandey, 2006). The efficacy of *P. herbarum* was tested on dandelion transplanted into an existing Kentucky bluegrass sward (Neumann & Boland, 1999). Significantly higher rates of dandelion foliage infection were observed in plants inoculated with *P. herbarum* strains formulated with potato dextrose broth together with either 5% durum semolina, 1% guar gum, or 5% gluten flour vs. a potato dextrose broth control 3 wk

postinoculation. Field conditions reduce the efficacy of *P. herbarum* to infect dandelion (Schnick & Boland, 2004). The authors observed that in the spring trial, foliage infection rates were lower because dandelion was able to outgrow the disease. Therefore, it is unclear if *P. herbarum* is capable of imposing a long-term fitness cost on dandelion.

*Phoma macrostoma* was isolated from Canada thistle [*Cirsium arvense* (L.) Scop.] and caused chlorosis and bleaching of young leaves in broadleaf weeds by producing phytotoxic macrocidins (Graupner et al., 2003, 2006). Differences in efficacy of *P. macrostoma* on broadleaf weeds were reported by Smith et al. (2013, 2015) with dandelion being most effectively controlled. Weeds have a very low risk of developing resistance to macrocidins isolated from *P. macrostoma* because of their diverse modes of action (Hubbard, Taylor, Bailey, & Hynes, 2016). According to Boerema, de Gruyter, Noordeloos, and Hamers (2004), *P. macrostoma* is a weak and opportunistic pathogen, which enters host plants through wounds. *Phoma macrostoma* 94-44B was granted full registration in Canada to be sold and used for the control of a broad spectrum of broadleaf weeds found in turfgrass (Hynes, 2018). Mycelial fragments of *P. macrostoma* applied to soil caused photobleaching and death to dandelion but had no effect on monocotyledonous weeds (Bailey & Derby, 2001). For broadleaf weed control in turfgrass the *P. macrostoma* isolate 94-44B was formulated into a granule for soil applications to act as a pre- and postemergence biological herbicide (Bailey, Pitt, Leggett, Sheedy, & Derby, 2011). Field trials conducted at three locations (silt-loam, pH 7.1; sandy loam, pH 7.8; and silt loam pH 7) in Canada, with high dandelion densities reported an average reductions of dandelion ranging from 70–90% in summer and late fall. Product efficiency was further increased by 10–20% when N treatments were added (Bailey, Falk, Derby, Melzer, & Boland, 2013). Year-to-year efficiency of *P. macrostoma* was influenced by environmental conditions, soil type, and organic matter content. Negative interactions between *P. macrostoma* and sulfate applications were observed, which reduced efficiency of dandelion control (Bailey et al., 2013). Currently no data are available on the efficiency of *P. macrostoma* to control other common turfgrass weeds.

*Sclerotinia minor* is the causal agent of lettuce drop (Wymore & Lorbeer, 1987). The fungus produces sclerotia that survives in the soil. *Sclerotinia minor* can infest a wide range of host plants including common turfgrass weeds such as dandelion, white clover, and broadleaf plantain (*Plantago major* L.) (Harding & Raizada, 2015). The isolate IMI344141 was identified as suitable candidate for the production of bioherbicides (Briere, Watson, & Hallett, 2000). During pathogenesis oxalic acid accumulates in the host plant and synergistically enhances the effect of pectolytic enzymes (Marciano, Di Lenna, & Magro, 1983).

Mycelia of *S. minor* require a susceptible host to persist in the environment, otherwise they decay after 10 d when applied to turfgrass areas (Watson, 2007). A Kentucky bluegrass sward treated with an inoculum of a *S. minor* strain six times during the first year and four times during the following year resulted in a reduction of 80.7% of dandelion (Riddle, Burpee, & Boland, 1991). A subsequent 3-yr field study showed that *S. minor* was as effective at controlling white clover, broadleaved plantain, birdsfoot trefoil, and common ragweed (*Ambrosia artemisiifolia* L.) as the herbicide Killex (active ingredients: 2,4 D; mecoprop and dicamba) (Abu-Dieyeh & Waston, 2007).

## 6.2 | Bacterial based herbicides

Propagation of bacteria is less dependent on environmental influences than to fungi (Li et al., 2003) and is therefore more rapid and more suitable for potential genetic modifications (Harding & Raizada, 2015; Johnson, Wyse, & Jones, 1996; Li et al., 2003). Several bacterial strains of *P. fluorescens* were identified as agents to control annual bluegrass and certain graminaceous plants (Banowetz, Azevedo, Armstrong, & Mills, 2009; Kennedy, 2016). Soil-applied bacteria, such as *P. fluorescens* strain D7, produce a complex of a lipopolysaccharide and extracellular peptides, which inhibit root and shoot growth of annual bluegrass but no other turfgrass species (Gurusiddaiah, Gealy, Kennedy, & Ogg, 1994; Kennedy, 2016). Furthermore, the *P. fluorescens* strain WH6 produces oxyvinylglycines and therefore inhibits germination of a broad range of plants (Banowetz et al., 2009). Fall applications of the bacterium led to establishment in the soil and propagation during cool temperatures similar to annual bluegrass root growth. Therefore, *P. fluorescens* has potential to be developed into a selective postemergence soil spray to reduce the annual bluegrass seed bank in turfgrass swards (Kennedy, 2016). Johnston and Golob (2017) found that *P. fluorescens* applications to an annual bluegrass and Kentucky bluegrass golf fairway made in fall 2015 and spring 2016 were ineffective at controlling annual bluegrass. Currently *P. fluorescens* strain D7 is registered for the control of agricultural weeds but not annual bluegrass (USEPA, 2014).

Strains of the Gram-negative bacterium *Xanthomonas campestris* cause bacterial wilt on susceptible plants (Imaizumi, Nishino, Miyabe, Fujimori, & Yamada, 1997). Bacteria of *X. campestris* enter host plants through natural openings such as stomata or wounds and multiply in intercellular spaces or the xylem. Pathogenicity is caused by the injection of effector proteins or the manipulation of the plant transcriptome by mimicking



transcriptional activators (Kay & Bonas, 2009). In Japan, *X. campestris* pv. *poannua* was formulated into a commercially available product (Nishino & Tateno, 2000). The bacterium is host specific for annual bluegrass and does not affect other turfgrasses (Fujimori, 1999; Zhou & Neal, 1995). In field tests, annual bluegrass abundance was reduced by 40% when *X. campestris* pv. *poannua* formulated as a spray was repeatedly applied (Zhou & Neal, 1995). However, 2–5 wk after discontinuing applications recovery occurred. Johnson et al. (1996) found that infection of annual bluegrass in bermudagrass golf greens only occurred when *X. campestris* pv. *poannua* was applied with a surfactant and during mowing. Six monthly applications resulted in 70% control of annual bluegrass (Johnson et al., 1996).

### 6.3 | Organic products with herbicidal mechanisms

Corn gluten meal derived from maize (*Zea mays* L.) produces allelopathic chemicals such as benzoxazinoids, which inhibit root growth, enzyme activity, and germination of annual grassy weeds and agricultural weed plant species such as okra [*Abelmoschus esculentus* (L.) Moench] (Ayeni & Kayode, 2013; Christians, 1991; Jabran & Farooq, 2013). Other herbicidal activity is likely to be caused by multiple dipeptides, which have an inhibitory effect on weed seed germination (Baker & Grant, 2018; Unruh, Christians, & Horner, 1997).

In greenhouse studies, corn gluten meal showed effective herbicidal activity on black medic (*Medicago lupulina* L.), buckhorn plantain (*Plantago lanceolata* L.), dandelion, crabgrass, and other common turfgrass weeds (Baker & Grant, 2018). However, other studies question the claims of herbicidal activity and suggest that the N concentrations in corn gluten meal simply give turfgrasses a competitive advantage over weeds that allows them to reduce dandelion, crabgrass, and clover densities (Christians & Dant, 2005; John & DeMuro, 2013; Patton & Weisberger, 2012). In another study, liquid corn gluten meal showed no herbicidal effect on weeds in turfgrass trials (Lyons, Jordan, & Carey, 2015). The conclusion that can be drawn from these studies is that corn gluten meal can be used as an organic N source but not as an herbicidal alternative to control weeds in turfgrass settings.

Acetic acid is produced by aerobic bacteria, during the fermentation of ethanol containing plant material (Webber, Harris, Shreffler, Durnova, & Christopher, 2005). Acetic acid applied to turfgrass causes the nonselective breakdown of foliage (Webber & Shreffler, 2006). In the United States, acetic acid products with <8% concentration do not have to be registered and are effective in con-

trolling young weeds with one to two leaves (Webber & Shreffler, 2006). Improved control can be achieved by using higher rates of 20% acetic acid and increasing application volumes (Webber & Shreffler, 2006). The effectiveness of acetic acid in controlling weeds is also dependent on maximizing the area of contact with the foliage, which will be determined by the growth habit of the weed and the method of product application (Evans, Bellinder, & Goffinet, 2009).

## 7 | THERMAL WEED CONTROL

Thermal weed control can be used to sterilize a seedbank or spot spray or burn existing weeds. Hoyle, McElroy, and Rose (2012) documented good broadleaf and grassy weed but less yellow nutsedge (*Cyperus esculentus* L.) control before tall fescue establishment when using an enclosed flaming system. The authors reported that 6 wk after seeding, tall fescue reached >60% establishment when flaming was applied in fall vs. summer. In agriculture, steaming soil with 70–100 °C water steam to a depth of 10 cm for 3–8 min is used to kill weed seeds in soil (Bond, Turner, & Grundy, 2003). During such a sterilization process, microorganism abundance is reduced for at least 2 mo and the community function might change after recovery (Roux-Michollet et al., 2008). Steaming soil could be an alternative to pre-emergence herbicides to treat newly constructed turfgrass areas. For spot treatments, hot water was successfully used to reduce common broadleaf dock (*Rumex obtusifolius* L.) by 80% without causing damage to the soil structure (Latsch, Anken, Herzog, & Sauter, 2017). Large patches of weeds can also be treated with solarization. Solarization requires covering patches of weed with plastic covers during favorable conditions. After some time, heat and solar radiation injures weeds but also dries out the seedbank (Horowitz, Regev, & Herzlinger, 1983). However, this method might only be appropriate for small turfgrass areas because installing covers is labor intensive and covers need to be in place for several days. Other thermal weed control methods include freezing, electric currents, irradiation, microwave radiation, and ultraviolet light.

Targeted mechanical or thermal weed control in large turfgrass areas would require high-resolution field scouting systems to initially detect weeds (Bell, Kurse, & Krum, 2013). In a next step, automated systems could be developed to remove the weed. Weeds can be removed by laser treatment (Mathiassen, Bak, Christensen, & Kudsk, 2006) or hot water (95 °C), which was more effective to spot treat weeds than flaming, steam, hot air, and steel brushing (Kristoffersen, Rask, & Larsen, 2008).

## 8 | PERSPECTIVE ON NONCHEMICAL WEED CONTROL

A complete ban of herbicides will most likely require a change in perception of weeds and playing quality expectations. In cases where herbicides are banned, weeds may have to be treated only if they interfere with playing quality. In such occasions, threshold levels need to be established to determine which types of weeds need to be treated, in which playing areas, and at what infestation level (e.g. percentage of playing area covered by weeds). Treating weeds solely for aesthetic reasons will most likely no longer be an acceptable justification for legislators. If users of turfgrass areas still object to the presence of weeds for mainly aesthetic reasons, a stronger effort needs to be placed on convincing legislators as to why weeds interfere with the purpose of the area and why they need to be removed.

Future research should focus on assessing the competitiveness of certain turfgrass species and cultivars against weeds under different maintenance regimes and within the limitations of producing turfgrass areas of acceptable playing quality. The literature suggests that broadleaf weeds are reduced when more N is applied; therefore, finding a balance between what is needed and what is environmentally safe and sustainable is critical. In the context of achieving sustainability, increased attention has been placed on fertilization needed by turfgrass areas. The prevailing opinion of the public in general and legislators in particular has been that turfgrass in general and golf courses in particular are overfertilized (May, Hall, Chalmers, & Carry, 2009), and for this reason, minimum levels for sustainable nutrition could be used as guidelines (Woods, Stowell, & Gelernter, 2014). These guidelines were developed and published from a data set of over 16,000 soil samples that were collected on turfgrass that was of acceptable quality (PACE Turf, 2014). However, since most of these soil samples were collected in the United States, it might be fair to assume that herbicides were applied as part of the maintenance. Consequently, caution needs to be used when minimum levels for sustainable nutrition standards are applied but herbicides are not available for weed control.

In the future, the best approach for turfgrass managers might be to use remote sensing technology to detect deficiencies such as poor irrigation uniformity, soil compaction, and nutrient deficiencies. Improving overall plant health will encourage dense growth of turfgrasses and increases the competitive ability of turfgrasses to suppress weeds. Precision turfgrass management might be a useful tool to address these issues. Unmanned aerial vehicles or autonomous ground-based sensing vehicles equipped with cameras, multispectral sensors, remote sensors, or

other equipment can be used to collect data about turfgrass health such as monitoring water stress, nutrient deficiencies, pest pressure, and salinity (Carrow, Krum, Flitcroft, & Cline, 2010; Caturegli et al., 2016; Krum, Carrow, & Karnok, 2010; Stowell & Gelernter, 2006). Spectral reflectance can provide information about leaf-area index, chlorophyll content, biomass, drought stress, and nutritional status (Agati et al., 2013; Caturegli et al., 2015; Finke, 1992; Foschi, Volterrani, Grossi, & Miele, 2009). Satellite remote sensing can also be used to assess N status of turfgrasses spatially and in real time (Caturegli et al., 2015). In the future, normalized difference vegetation index sensors would ideally be mounted to mowing units to collect data in near real time. These technologies may be able to detect deficiencies and poor quality or sparse turfgrass but are unable to pinpoint the cause of the inadequacies. For example, to determine optimal (or minimal) fertilizer requirements, soil sampling or leaf tissue analysis is still needed. Moreover, precision fertilization practices include zoning a golf course into site-specific management units, where areas with similar usages, soil compositions, topography, plant responses, and microclimates are zoned (Krum et al., 2010). A composite soil sample could be taken from each zoned area to analyze soil nutrient status, which requires less sampling than grid sampling (Carrow et al., 2010; Ikenaga & Inamura, 2008; Johnson et al., 2001; Shaner, Khosla, Brodahl, Buchleiter, & Farahani, 2008). A sensible approach might be to use soil sampling site-specific management units to measure the soil pool of rather immobile nutrients, such as P and K (Giehl & Wirén, 2014), and to use remote sensing techniques on a more frequent basis to measure mobile nutrient status such as N.

The most effective method of removing existing weeds in turfgrass swards without the use of synthetic herbicides might be to spot spray with hot water or high concentrations of nonselective biological products such as acetic acid. Host-specific biological products based on fungi or bacteria are only available in selective countries around the world, and their efficiency is questionable. Much effort is ongoing to increase the efficacy of these products and they might become viable options to synthetic herbicides in the future. Thorough testing, including controlled screenings and field trials, are needed to provide information about the host-specific persistence of biological products in changing environments over time. The development of robotic machines to detect and remove weeds might be one of the more promising approaches to control weeds in the future. Detecting and removing weeds in dense turfgrass swards is challenging but currently under development.

Sustainable turfgrass management will become increasingly important for budgetary and environmental reasons; however, approaches that address both objectives (cutting


cost and environmental protection) are not always possible as they can be mutually exclusive. Therefore, if synthetic herbicides (or pesticides in general, for that matter) are being banned from use on turfgrass areas, future research is needed to develop maintenance strategies that include minimum levels for sustainable nutrition guidelines that focus on outcompeting weeds and on the prevention of turfgrass pests in general.

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## ORCID

Daniel Hahn  <https://orcid.org/0000-0002-7513-747X>

Rossana Sallenave  <https://orcid.org/0000-0003-2420-9282>

Bernd Leinauer  <https://orcid.org/0000-0002-3700-2005>

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