

**INFLUENCE OF ANNUAL BLUEGRASS ON PUTTING GREEN TRUENESS, AND
CONTROL OF WEEDY POA SPECIES IN KENTUCKY BLUEGRASS AND
CREEPING BENTGRASS TURF**

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Influence of Annual Bluegrass on Putting Green Trueness, and Control of Weedy *Poa* Species in Kentucky Bluegrass and Creeping Bentgrass Turf

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ABSTRACT

Annual bluegrass (*Poa annua* L.) and roughstalk bluegrass (*Poa trivialis* L.) are among the most troublesome grass weeds on golf courses throughout the United States. Herbicides for selective control of these weeds in cool-season fairways are limited and ineffective. Methiozolin is a new isoxazoline herbicide that controls annual bluegrass on putting greens and shows promise for possible weed control in fairways. Kentucky bluegrass (*Poa pratensis* L.) is among the most common turfgrass species used for golf fairways in the Northern United States and its response to methiozolin has scarcely been tested. A 2.5-yr field study was conducted at four Virginia locations to evaluate methiozolin efficacy for selective annual bluegrass and roughstalk bluegrass control in creeping bentgrass (*Agrostis stolonifera* L.) or Kentucky bluegrass fairways. Another study evaluated the response of 110 Kentucky bluegrass varieties to three rates of methiozolin.

Annual bluegrass has long been presumed to impact putting green trueness, or the ability of the greens canopy to provide a smooth and directionally-consistent ball roll. Although much research has evaluated the impact of greens management on ball roll distance, no peer-reviewed research has evaluated how canopy surface factors, such as weedy annual bluegrass, will influence ball roll direction. Laboratory and field research was conducted to elucidate and overcome experimental errors that may be limiting assessment of ball directional imprecision caused by greens canopy anomalies. Techniques to minimize experimental error were employed in field studies at two Virginia golf courses to determine the influence of annual bluegrass on ball directional imprecision, bounce, and acceleration.

Study results suggest that annual bluegrass patches in a creeping bentgrass putting surface can cause subtle increases in ball directional imprecision and bounce but several sources of error must be controlled before these effects can be measured. By using a mechanical putter to avoid directional errors associated with simulated-putt devices, selecting golf balls with balanced centers of gravity, eliminating legacy or "tracking" effects of repeated ball rolls via canopy brushing, and scoring ball direction 30 cm prior to terminal acceleration, we were able to detect an increase in ball directional imprecision of 8 mm m⁻¹ when balls rolled over a single patch of annual bluegrass compared to adjacent rolls on visually-pure creeping bentgrass.

In herbicide efficacy studies, methiozolin-only treatments did not significantly injure creeping bentgrass or Kentucky bluegrass, reduce quality, or reduce normalized difference vegetative index regardless of application timings and rates. In general, fall applications of methiozolin reduced roughstalk bluegrass and annual bluegrass cover more than the spring-only treatments. At 1 year after the last treatment, methiozolin at 1500 g ha⁻¹ applied four times in fall at 2-wk intervals for two consecutive years controlled roughstalk bluegrass and annual bluegrass $\geq 85\%$ and more consistently than other herbicides or treatment regimes. Spanning 110 Kentucky bluegrass varieties, a commercially-acceptable threshold of 30% Kentucky bluegrass injury required between 3.4 to more than 10 times the methiozolin rate needed for annual bluegrass control. Results indicate that annual bluegrass increases directional imprecision and bounce of golf balls rolling across a greens canopy. Methiozolin could be a viable herbicide for managing

annual and roughstalk bluegrass in Kentucky bluegrass and creeping bentgrass fairways but weed control efficacy may be dependent on application timing. By measuring small differences in ball directional imprecision as influenced by greens canopy factors, future research efforts will aim to help turf managers choose appropriate greens management techniques.

Management of Weedy Bluegrass Species in Kentucky Bluegrass and Creeping Bentgrass Turf, and Influence of Annual Bluegrass on Putting Green Trueness

Sandeep Singh Rana

GENERAL AUDIENCE ABSTRACT

Annual bluegrass and roughstalk bluegrass are among the most troublesome grass weeds on golf courses throughout the United States. Both these weedy bluegrass species reduces the aesthetics and playability of golf turf, including fairways, tees, and putting greens. Since both annual bluegrass and roughstalk bluegrass favors growing conditions very similar to that of desirable cool-season grasses, especially Kentucky bluegrass and creeping bentgrass – the most prominent cool-season grasses on golf courses throughout the Northern USA, selective removal of these weedy bluegrass species from the desirable turf sward is very difficult. Moreover, genetic similarity of annual bluegrass and roughstalk bluegrass to Kentucky bluegrass accentuates the difficulty in selective control even more.

Commercially-available herbicides for selective control of these weedy bluegrass species in cool-season golf fairways are limited and often ineffective for long-term control. Methiozolin (PoaCure®) is a new herbicide that has been extensively studied and shown to control annual bluegrass on golf putting greens and shows promise for possible weed control in fairways. However, PoaCure® has scarcely been tested to selectively and safely control annual bluegrass and roughstalk bluegrass in cool-season golf fairways. Therefore, field research was conducted at four Virginia locations to evaluate PoaCure® efficacy for selective, long-term annual bluegrass and roughstalk bluegrass control in creeping bentgrass or Kentucky bluegrass fairways. To assess the weed-control potential of PoaCure® on a broader spectrum of Kentucky bluegrass varieties grown here in VA and other cool-season grass growing parts of the nation, another field research was conducted to evaluate the response of 110 Kentucky bluegrass varieties to three different field application rates of PoaCure®.

In PoaCure® weed control efficacy studies, PoaCure® by itself did not injure or reduced quality of creeping bentgrass or Kentucky bluegrass regardless of application timings and rates. In general, fall applications of PoaCure® reduced roughstalk bluegrass and annual bluegrass green cover more than the spring-only treatments. At trial completion, which was 2.5 years after trial initiation and 1 year after the last herbicidal treatment, PoaCure® at 82 fl oz/A applied four times in fall at 2-wk intervals for two consecutive years provided $\geq 85\%$ control of annual bluegrass and roughstalk bluegrass and did so more consistently than other herbicides or treatment regimes in the study. In the tolerance study of 110 Kentucky bluegrass varieties, a commercially-acceptable threshold of 30% injury required between 3.4 to more than 10 times the PoaCure® rate needed for annual bluegrass control. Results from herbicide efficacy and tolerance studies indicate that PoaCure® could be a viable herbicide for managing annual and roughstalk bluegrass in Kentucky bluegrass and creeping bentgrass fairways but weed control efficacy may be dependent on application timing.

In addition to being difficult to control and aesthetically unpleasing to view, annual bluegrass has also long been blamed for missed golf putts. Some researchers have surmised that a golf ball's direction may be altered when the ball traverses an anomaly in the greens surface,

such as annual bluegrass, but no scientific studies have tested this assumption. Laboratory and field research was conducted to elucidate and overcome experimental errors that may be limiting assessment of ball directional imprecision caused by greens canopy anomalies. Study results suggest that an isolated patch of annual bluegrass increases ball directional imprecision by 8 mm m^{-1} compared to visibly-pure creeping bentgrass and that tools and methodology currently reported in scientific literature are not precise enough to discern these subtle changes in direction.

At Virginia Tech, we devised a new methodology to discern subtle changes in ball roll directional precision and bounce as influenced by an isolated patch of annual bluegrass in an otherwise visually-pure creeping bentgrass canopy. We used a mechanical putter to minimize directional errors associated with commercially-available simulated putt-devices, selected balanced golf balls, eliminated legacy of repeated ball rolls by brushing putting green surface canopy between ball rolls, scored ball direction prior to terminal acceleration with pressure-sensitive paper, and used high-speed video and motion tracking software to measure ball wobble and bounce. Results indicate that annual bluegrass increases directional imprecision and bounce of golf balls rolling across a greens canopy.

“Nothing in this world can take the place of persistence. Talent will not; nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education will not; the world is full of educated derelicts. Persistence and determination alone are omnipotent. The slogan Press On! has solved and always will solve the problems of the human race.”

- Calvin Coolidge

Dedicated to my amazing wife, Trisha Sanwal Rana

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Chapter 1. Introduction and Literature Review

Annual bluegrass (*Poa annua* L.) and roughstalk bluegrass (*Poa trivialis* L.) are among the most troublesome and difficult to control grass weeds in golf turf (Bell et al. 1999). Both annual bluegrass and roughstalk bluegrass are cool-season grasses that originated in Europe (Beard 1973) and were possibly introduced to the United States as seed contaminants of desired turfgrasses, like Kentucky bluegrass (*Poa pratensis* L.) and creeping bentgrass (*Agrostis stolonifera* L.) (Beard 2001; Hurley 2003; Levy 1998). Both the weedy *Poa* species are light-green in color and sensitive to extremes of summer and winter, salt, insects, and diseases, and lead to reduced aesthetic beauty and functionality of turf and increased management costs (Beard 1973; Carrow and Duncan 1998; Christians 2004; Hurley 2003). However, under suitable conditions, both the weedy *Poa* species can outgrow the majority of desirable cool-season grasses.

Annual bluegrass and roughstalk bluegrass both have folded vernation, boat-shaped leaves, and light-green color (Beard 1973) making them hard to distinguish. Generally, roughstalk bluegrass emerges prior to annual bluegrass in spring and enters dormancy before annual bluegrass in summer. Annual bluegrass typically becomes more noticeable around May and June when it produces a flush of unsightly whitish-green seedheads; whereas, roughstalk bluegrass rarely produces seedheads when mowed in a managed turf (Reicher et al. 2006; Patton and Beck 2014).

Roughstalk bluegrass forms a yellowish-green and fine textured turf of high shoot density that produces leafy stolons (Beard 1973; Hurley 2003). Under certain limited environmental conditions, roughstalk can grow aggressively to form distinct patches that dominate and do not

blend well in polystands (Beard 1973; Fry and Huang 2004; Hurley 2003). However, when managed under suitable environmental conditions and cultural practices, roughstalk bluegrass can form a dense and uniform turf (Beard 1973) that can be used as an overseeded species on golf courses in the southern United States (Morton 2008). Roughstalk bluegrass has a high amount of genetic variability because of cross-pollination (Beard 1973; Hurley 2003). From the time roughstalk bluegrass was introduced to the United States till now, researchers had exploited its genetic variability to produce several improved cultivars (Hurley 2003). For commercial purposes, roughstalk bluegrass is recommended for lawns and pastures with cool, moist, and shaded environments that are not subjected to concentrated traffic (Beard 1973), and for winter overseeding programs on bermudagrass (*Cynodon* spp.) turf in the southern United States (Fry and Huang 2004; Hurley 2003).

Whether roughstalk bluegrass is present as a wanton weed or desirable turf, it has a higher low-temperature tolerance and lower heat and drought tolerance compared to commonly used cool-season turfgrasses (Beard 1973; Hurley 2003; Sifers and Beard 1993). Roughstalk bluegrass has now naturalized in most of the North America (Hurley 2003). The naturalized populations of roughstalk bluegrass can spread vegetatively via routine cultural practices and human activities; whereas, the commercially-improved varieties presumably spread as seed contaminants (Levy 1998; Reicher et al. 2011). Roughstalk bluegrass's ability to spread both vegetatively and via seeds poses a serious threat of infestation to the managed turf areas and seed lots. Levy (1998) and Reicher et al. (2011) found roughstalk bluegrass contamination in 30 and 11% of 90 and 72 seed lots of creeping bentgrass tested in their respective studies.

Once roughstalk bluegrass enters a golf course, highly maintained fairways that have abundant water favor the aggressive growth of roughstalk bluegrass that can outgrow desirable species while reducing the overall aesthetics and functionality of fairways (Beard 1973; Hurley 2003). Although roughstalk bluegrass can go unnoticed in a mixed stand of other cool-season grasses, especially creeping bentgrass, under favorable environmental conditions and cultural practices, it ought to go dormant during the heat and drought stress of summer and possibly several other stresses leaving voided turf areas (Beard 1973; Fry and Huang 2004; Hurley 2003). The above literature indicates that roughstalk bluegrass is a developing problem in all managed turfgrass areas, including golf courses, athletic fields, home lawns, etc. Therefore, selective removal of roughstalk bluegrass from a stand of desired cool-season turfgrass is essentially the only option for maintaining aesthetics and functionality of the managed turfgrass areas over a long term.

Compared to roughstalk bluegrass, annual bluegrass is more troublesome and widely distributed species throughout the world, ranging from subtropical climates of Florida to near the equator and at higher elevations (Beard et al. 1978; Hemp 2008; Molina-Montenegro et al. 2012). Recently, annual bluegrass was recognized as the only non-native vascular plant that successfully established in the maritime Antarctic, an area characterized by low summer temperatures, inadequate liquid water, high season-light regime, and elevated UV-B radiations along with many other seasonally-related environmental stresses (Chown et al. 2012; Frenot et al. 2005). This ability of annual bluegrass to adapt to a wide range of environments makes it a cosmopolitan winter weed in managed turfgrass. Indeed, most of the top golf courses throughout the world have putting greens composed, at least in part, of annual bluegrass (Vargas and

Turgeon 2004). Tutin (1957) referred to annual bluegrass as the “supreme weed” because of its greater phenotypic variability than most weeds, ability to flower and fruit throughout the year, rapid germination, small enough size to escape notice, good survival on uprooting, easy seed dispersal by humans and implements, self-fertilization, and rapid life cycle.

Annual bluegrass is an allotetraploid resulting from a natural cross between *Poa supina* Schrad. ($2n = 2x = 14$ chromosomes), a creeping perennial, and *Poa infirma* H.B.K ($2n = 2x = 14$ chromosomes), an annual species, on the basis of morphology, cytology, and isozymes inheritance (Darmency and Gasquez 1997; Nannfeldt 1937). This natural cross between two species is the suspected source of genetic variability within annual bluegrass (La Mantia and Huff 2011) that helps successful colonization under a wide range of growing conditions. The allotetraploid ($2n = 4x = 28$ chromosomes) annual bluegrass is produced spontaneously when the sterile haploid restores its fertility via genome duplication. Although annual bluegrass is primarily considered to be an allotetraploid (Heide 2001; Tutin 1957), diploid forms have also been reported (Hovin 1957; Johnson et al. 1993). The diploid plants are generally dwarf, weak, male-sterile, and do not produce developed seeds (Johnson et al. 1993). The diploid populations provide the evidence of “reverse evolution” stimulated by intense selection pressure of the golf putting green environment (Huff 1999). Annual bluegrass is primarily an autogamous species with occasional outbreeding (15 to 22%) (Chen et al. 2003; Ellis 1973; Mengistu et al. 2000) but apomixes can also be observed in some individuals (Johnson et al. 1993).

Current literature on reproductive biology and ecology of annual bluegrass identifies it as an extremely variable species, ranging from annual (Grime 1979) or biennial (Tutin 1957; Warwick 1979) to perennial types (Lush 1989; Ruemmele 1989; Till-Bottraud et al. 1990). To

avoid confusion, the perennial form of annual bluegrass is named *Poa annua* var. *reptans* (Hausskn.) T. Koyama, an economically important component of the golf course industry worldwide (Huff 2003, 2010). Annual bluegrass exhibits several characteristics of an actively evolving species (Johnson et al. 1993). Indeed, researchers have identified the evolution of annual bluegrass from its wild, weedy, annual forms to the perennial forms adapted to golf, lawn, and athletic field turf as a classic example of rapid micro-evolution (Law 1977; Law et al. 1977; McNeilly 1981). The first invasion of annual bluegrass typically occurs on a golf course as an annual type that becomes established in damaged or weak open areas of turf (Huff 2004). However, extreme selection forces of turf management, phenotypic plasticity of annual bluegrass, and cross-pollination events facilitates annual bluegrass to evolve as a perennial type over a period of time (Huff 2004). Perennial or greens-type annual bluegrass can be seen to appear on golf courses as young as 10-years old (Huff 2004).

The major selection pressures acting on annual bluegrass on a golf course, especially on putting greens, are low mowing heights, moisture availability, and high fertility (Huff 2004). The selection forces of a putting green environment are so intense that on greens which are 60 years old, it is common to find dihaploid forms of annual bluegrass, which are sterile with occasional flower stalk production, and exists entirely as a vegetative perennial (Huff 1999). The perennial type of annual bluegrass can have characteristics, such as increased tiller density, that make it a desirable golf turf rather than a wanton weed (Wu et al. 1992). On roughs and fairways, annual bluegrass produces 3 to 8 tillers per flowering culm; however, on putting greens, tillers per culm varies from 9 to 52 (La Mantia and Huff 2011). Species variability and high adaptability have also made annual bluegrass resistant to several herbicides, including

glyphosate, endothall, simazine, amitrole, paraquat, atrazine, cynazine, prometryn, terbutryn, ethofumesate, pendimethalin, prodiamine, bispyricbac-sodium, foramsulfuron, imazaquin, norfluzaron, and trifloxysulfuron-sodium (Heap 2016).

In addition to disrupting aesthetics of desired turfgrass on a golf course, annual bluegrass has long been blamed for increased putting green surface inconsistencies and perceived reduction in ball roll distance and directional consistency (Cross 2014; Oatis 2013; Piper and Oakley 1921). Prolific seedhead production further adds to the complaints against annual bluegrass for disrupting putting green uniformity (Cross 2014; Oatis 2013). Although many researchers have speculated that annual bluegrass can negatively impact ball roll behavior on greens, no evidence could be found in the scientific literature to support these claims.

There are approximately 35,000 golf courses in the world, 50% of which are in the United States alone (Saito 2010). Despite the recent recession in the United States golf industry, the addition of golf to the Rio 2016 Olympics is a testament to a current global expansion in the \$68 billion golf industry. The game of golf is played entirely on turfgrass, with putting greens being the most time and money consuming entities, accounting for 60 to 70% of chemical and fertilizer expenditures (Drake 2014; Rist and Gaussoin 1997). Although putting greens constitute only about 3% of the total golf course turf, 70% of shots played in a round of golf are on and around putting greens (Lodge and Baker 1991). The putting stroke is the most common golf shot accounting for nearly half of all shots played in a round (Pelz 2000; Riccio 1990), and considered the single most important shot that defines professional golfer's earnings (Alexander and Kern 2005). Therefore, golf course superintendents strive for uniform and smooth greens for producing consistent putts (Drane et al. 2014).

Putting greens are managed to provide a uniform and reliable putting surface that gives golfers a fair chance of cupping the ball with a minimum number of putts. Once the golf ball leaves the face of the putter, it could either be airborne or bounce or it could be in a combined state of sliding and rolling on putting green's surface before achieving pure roll after covering approximately 20% of total putt length (Cochran and Stobbs 1968; Daish 1972; Penner 2001). The distance or time needed to achieve the pure roll depends on the loft of the putter, the relative position of the putter face at the time of impact, and firmness of the putting green surface (Brouillette 2010; Drane et al. 2014; Pope et al. 2014; Roh and Lee 2010). However, once the ball achieves pure roll, the putting green surface uniformity and smoothness are essentially the only factors that can influence ball's direction and distance.

Uniformity and smoothness are among the most important components of putting green quality according to Beard (1982) in his preeminent text on golf course management. Putting green "uniformity", however, is a largely misunderstood term. To a research agronomist, the term typically refers to consistency of texture and color of the putting green turf or to consistency of the intended turfgrass species or cultivar managed on the greens. To a golfer, the term "uniformity" implies consistency of ball roll speed and directional precision across all greens on the course. In the 1930's, Edward Stimpson invented a simple device for measuring the uniformity of ball roll speeds between greens within a golf course. In the 1970's, the United States Golf Association (USGA) conducted extensive tests on greens across the US and introduced the Stimpmeter (SM), a device based on Stimpson's original design. In subsequent years, the SM became the standard for measuring ball roll uniformity on putting greens. Putting greens are said to be uniform when ball roll distance does not vary more than 15 cm between

greens within a single golf course (Thomas 1983). The SM is a simple inclined plane with a groove that guides the ball down the center from a notch that releases the golf ball when the ball-holding end is raised to approximately 20° (Anonymous 2012a). The ball rolls down the SM and across a reasonably level area of greens canopy, and the roll distance is recorded in feet and referred to as the "stimp" (Anonymous 2012a).

The measurement of stimp with the SM has evolved from the original intent of ensuring uniformity of speed between greens on a given golf course to a benchmark for golfers expectations between courses, a research tool to characterize the impact of turf management practices on ball roll speed, and even a job responsibility for continued superintendent employment. However, measurements with the SM are subject to inconsistencies due to variable ball release between evaluators, random ball wobble on the device, ball bounce upon ball exit, and reduced friction when subsequent balls roll in the same track (Richards et al. 2009; Pelz 2002). In the SM user manual, the USGA indicates that the SM can lead to variability in ball roll distances, and balls deviating by more than 20 cm should be excluded from the average (Anonymous 2012a). Several researchers have utilized the SM to evaluate the influence of greens cultural practices, such as mowing, fertility, aeration, plant growth regulators, etc., on ball roll distances. In approximately 355 measured effects of greens cultural practices on ball roll distance in peer-reviewed literature, about 55% could not be separated statistically (Donald et al. 2013; Fagerness et al. 2000; Hartwiger et al. 2001; McCullough et al. 2005a, 2005b, 2005c; McCullough et al. 2006a, 2006b; Salaiz et al. 1995) presumably due to inherent variability of the SM.

David Pelz released the PELZmeter™ (PM) in 2003 with the aim of improving consistency of green speed measurements by reducing errors associated with the SM. The PM incorporates a spirit-level system to ensure the ball is released from a consistent height, a curvilinear ramp that releases the ball horizontally onto the green to minimize ball bounce, and three side-by-side grooves that help minimize legacy effects of previously-rolled balls (Anonymous 2004). However, Richards et al. (2009) reported no differences between PM and SM in putting green speed measurement.

Although the objective of the golf putt is both directionally and distally dependent, it is surprising that no to very little scientific data has been published that characterizes the influence of putting green surfaces on ball roll direction. Koslow and Wenos (1998) evaluated fluctuations in ball roll trueness across a green using a mechanical putting machine and reported that trueness can vary on a golf green from day to day and within the same day, depending on the time of day and traffic patterns. However, Koslow and Wenos (1998) did not assess the actual source of variation for trueness variability. Several researchers have implied that longer ball roll distances are indicative of smoother greens canopies that impart less frictional impact on ball roll behavior in general (Stahnke and Beard 1981; Samples and Sorochan 2008; Sweeny et al. 2000), but these claims are unsubstantiated. Moreover, there is currently no standard and quantitative method of determining putting green surface trueness (Linde et al. 2015).

Several trade magazine articles have reported visual assessment of putting green trueness using "roll" test, where a golf ball is rolled by hand across the green and visually rated for bounce and wobble (Buchen 1995; Linde 2005; Windows and Bechelet 2010). This method is far from ideal. Recently, the R&A golf organization has been promoting the "Hole Out" test

whereby turf managers can use a device called the Greenstester (GT), a curvilinear incline plane, to roll golf balls repeatedly towards a putting green cup and score the number of holed balls. At a particular setting, the GT can also be used to measure ball roll distance (Anonymous 2012b). The GT design suggests that on-device ball wobble could influence ball exit direction and repeatedly rolling ten balls on the same line, as per Hole-Out Test protocol, could impart a massive impact on ball directional behavior as each subsequent ball tends to follow the track created by the first ball (Anonymous 2004; Pelz 2002). Linde et al. (2015) reported that core cultivated greens canopies with or without sand topdressing, made balls bounce and wobble on the putting green surface; however, the majority of balls still rolled in the cup following the “Hole Out” test protocol and were no different than plots that received no surface-disrupting cultivation practices.

A different approach to measuring smoothness or trueness of putting green canopies utilizes devices that when rolled over the green surface, record positive, negative, and lateral G-forces of the rolling device. The ParryMeter, released in 2015, is a commercially-available device designed to transfer vertical and lateral movement of a golf ball into a platform that holds a smartphone/iPod when pushed across a green surface and generates smoothness and trueness measurement of the green (Anonymous 2014). The Sports Turf Research Institute Trueness/Evenness Meter (STRITM) is another device that uses a metal wheel instead of a golf ball to collect the vertical and lateral deviations (Baker and Spring 2010). This device is not available for sale but is used as a consulting tool by the inventors. McElroy et al. (2015) developed a Sphero Turf Research App that uses a robotic ball to assess surface smoothness and trueness using a similar measurement of lateral and vertical G forces. Although the ParryMeter,

STRITM, and Sphero seem to evaluate trueness and smoothness of putting green surfaces, no peer-reviewed science has evaluated their performance or correlated the data they generate to ball directional precision.

The dynamics of a golf putt depend on several factors, including putting accuracy (Drane et al. 2014); golf ball construction, dimple type and dimple pattern (Bowden et al. 2010; Lemons et al. 1999; Richardson et al. 2016); environmental conditions (Streich et al. 2015; Whitlark 2013); time of day and traffic patterns (Koslow and Wenos 1998); and putting green surface anomalies and cultural practices (Sweeny et al. 2000; Whitlark 2013). Although much is known about the physics of a golf putt, almost all research and technological innovations to date have been related to factors that may be controlled by the golfer (Penner 2002) or the putter design (Brouillette 2010; Butdee and Punpojmat 2007; Drane et al. 2014; Gwyn et al. 1996; Pope et al. 2014). After the golf ball achieves "true roll", the result of the putt is governed by the surface of the putting green, environmental conditions, and other factors that are not well characterized. Although several researchers have suggested that surface anomalies on putting greens can influence ball roll behavior, most of the information is either anecdotal or comes from non-peer reviewed trade magazine articles or similar resources (Karlsen et al. 2008; Pelz 2000; Swash 2001). The limited peer-reviewed research that is available addresses mainly ball roll distance or speed and limited research has been conducted to evaluate the influence of surface trueness on ball roll directional precision (Koslow and Wenos 1998).

Only one scientific paper has used techniques suitable for evaluating site-specific impacts on ball roll behavior. Researchers in Nebraska developed a novel and quantitative method to measure golf ball acceleration as influenced by mowing quality using a Stimpmeter attached to

the end of a semicircular, 1.8-m-long PVC pipe enabled with 10 photoelectric switches spaced at uniform intervals in the tube (Rist et al. 1999). As the golf ball was rolled through the tube, it activated the photoelectric switch and sent time data to the attached single-board computer. The known distance between the switches and time data were then used to compute ball roll acceleration five times over a 1.8-m distance. This methodology was used in the field to compare among different mowing treatments (unmowed, once-mowed, and twice-mowed) and golf ball rolling directions (2 directions opposite to each other). Results of this study indicated that some differences in ball acceleration were possible between mowing treatments, but no actual ball roll distance, speed, and acceleration data were presented in the paper. Moreover, two out of three mowing treatments tested in the study were considered impractical for today's golf courses. Finally, the Rist et al. (1999) paper, like all other scientific works related to ball roll, measured only factors that govern ball roll speed or distance with no attention given to ball roll direction.

The recent marketing and evaluation of devices such as the GT, ParryMeter, STRITM, and Sphero indicate that there is a growing interest in evaluating putting green trueness. Therefore, it is imperative to scientifically test how surface imperfections on a putting green can interfere with surface uniformity and trueness to influence ball directional consistency. We hypothesized that a putting green surface imperfection, such as an infestation of weedy annual bluegrass, will increase directional imprecision of balls rolled over it. We further assumed that specialized methods would be needed to produce repeatable ball rolls that accurately reflect the influence of green's canopy on the ball roll. Our objectives were 1) to assess the influence of golf ball brand on ball center of gravity, 2) to determine the influence of ball brand and

simulated-putt device on ball roll directional and distal imprecision, 3) to determine if repeatedly rolling balls in the same line will impact distal and directional imprecision, and if brushing the canopy between rolls will control this potential source of error, and 4) to demonstrate the influence of annual bluegrass on ball directional imprecision and bounce.

Regardless of annual bluegrass impact on ball directional imprecision and bounce, annual bluegrass is the most troublesome grass weed on golf courses that warrants an effective, selective, and long-term control. Annual bluegrass used to be considered as component of many turf stands before 1950s; however, the increased expectations for sports turf and golf courses thereafter drove the research focus towards selective control options for annual bluegrass (Gibeault 1974). Research for chemical control of annual bluegrass started as early as 1930's (Sprague and Burton 1937) and continued to be a major challenge for researchers (Cross et al. 2012; Lycan and Hart 2006; Park et al. 2002; Woosley et al. 2003) and turf managers till Koo et al. (2013) at Moghu Research Center discovered the specificity of methiozolin for annual bluegrass and roughstalk bluegrass in turfgrass. For past six years, methiozolin has been extensively researched for efficacy controlling annual bluegrass on creeping bentgrass greens (Askew and McNulty 2014; Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013). However, there is no peer-reviewed paper till now that reports methiozolin efficacy for selective and long-term control of annual bluegrass and roughstalk bluegrass in fairway-height (1.3-cm on an average) turf.

Although cultural practices and plant growth regulators can be used to suppress annual bluegrass and roughstalk bluegrass (Aldahir et al. 2015; Haguewood et al. 2013; Thompson et al. 2016), effective and long-term control relies primarily on selective herbicides. Postemergence

roughstalk bluegrass control in the cool-season turf is limited to spot treatment with nonselective herbicides, like glyphosate, followed by reseeding with desired turfgrass (Liskey 1999; Morton et al. 2007). Mueller-Warrant (1990) reported late-winter to late-spring applications of fenoxaprop to control roughstalk bluegrass in perennial ryegrass but the efficacy varied among seasons with poor performance from applications made before winters. Moreover, better roughstalk bluegrass control with late-spring applications came at the expense of increased injury to perennial ryegrass (Mueller-Warrant 1990). Additionally, rates of fenoxaprop needed to control roughstalk bluegrass are too injurious to creeping bentgrass; thereby, limiting use on golf courses (Anonymous 2011a).

Morton et al. (2007) evaluated bispyribac-sodium and sulfosulfuron for roughstalk bluegrass control in creeping bentgrass but because of differences in cultivar sensitivity, application timings, and temperatures across yr and locations, turf and weed response were variable and not conclusive enough to recommend a single best strategy. The dependency of bispyribac-sodium and sulfosulfuron efficacy on temperature, with better performance under warm temperatures, has also been reported by other researchers (Lycan and Hart 2006; McCullough and Hart 2006). Thompson et al. (2016) evaluated bispyribac-sodium, paclobutrazol, and tank-mixtures of amicarbazone and mesotrione for roughstalk bluegrass control, and reported that only bispyribac-sodium effectively controlled roughstalk bluegrass. Summer applications of bispyribac-sodium at 74 g ha^{-1} applied three times at 2-wk intervals controlled roughstalk bluegrass 14 to 90% depending on location when assessed 3 to 4 months after initial treatment (Thompson et al. 2016). In lawn-height (7.6 cm) turf, McNulty and Askew

(2011) reported 90% roughstalk bluegrass control with sequential applications of bispyribac-sodium at 74 g ai ha⁻¹ at 4 wk after treatment (WAT) but no control was evident one year later.

Primisulfuron, a sulfonylurea herbicide not labeled for use in turf, at 26.3 g ha⁻¹ has been reported to control roughstalk bluegrass 83% at 3 WAT (Post et al. 2013). Amicarbazone is a newer herbicide for annual and roughstalk bluegrass that has also been reported by Landry et al. (2011) to control weedy bluegrass species 70% and better than bispyribac-sodium and sulfosulfuron. However, amicarbazone at 0.5 kg ha⁻¹ injured creeping bentgrass 65% and reduced stand density 45%, 3 WAT. By 6 WAT, turf injury was less than 20% from all three rates of amicarbazone used in the experiment (Landry et al. 2011).

Postemergence annual bluegrass control options in cool-season turf are limited to bispyribac-sodium, ethofumesate, amicarbazone, and tenacity. Bispyribac-sodium produces inconsistent turf safety and annual bluegrass control due to seasonal variability in application timing and temperature (Hart and McCullough 2007; Lycan and Hart 2006; McCullough and Hart 2006). McNulty and Askew (2011) reported bispyribac-sodium to injure Kentucky bluegrass 60% 9 d after treatment (DAT) and control annual bluegrass less than 40% by 7 WAT. McCullough and Hart (2006) also reported temperature to significantly influence bispyribac-sodium safety to creeping bentgrass and efficacy to control annual bluegrass with better control and minimal injury at warmer temperatures of 20 to 30 C but an opposite response at 10 C. Bispyribac-sodium also causes significant injury to Kentucky bluegrass under traffic and shade (Anonymous 2010).

Ethofumesate has also been reported to control annual bluegrass postemergence by causing irreversible cell division abnormalities (Haggar and Passman 1981; Jukes and Goode

1981; Lee 1977; Lee 1981; Shearman 1986; Woosley et al. 2003). However, researchers have found conflicting results for efficacy of ethofumesate in controlling annual bluegrass with safety to desired cool-season turf. Lee (1981) reported ethofumesate at 1.1 kg ha^{-1} , a rate lower than that needed for annual bluegrass control (Jukes and Goodes 1981), to eliminate stand counts of several cool-season turfgrasses. Mesotrione is also reported to control annual bluegrass PRE or POST (Anonymous 2011b; Askew et al. 2003). Skelton et al. (2012) have reported frequent and sequential applications of mesotrione at 0.11 kg ha^{-1} or less to control annual bluegrass up to 95%. However, Reicher et al. (2011) noted erratic annual bluegrass control from the sequential application of mesotrione at 0.28 and 0.39 kg ha^{-1} .

The inability of currently-available herbicides and lack of knowledge about the selectivity of methiozolin for controlling annual bluegrass and roughstalk bluegrass in cool-season golf fairways warrants the need of evaluating methiozolin in golf fairways. Therefore, field trials were conducted with the objective of evaluating the response of creeping bentgrass and Kentucky bluegrass injury, cover, and normalized difference vegetative index (NDVI); annual bluegrass and roughstalk bluegrass control, cover, and NDVI; and turf NDVI and quality following methiozolin applications at several different timings and tank-mixtures.

The efficacy of methiozolin to control annual bluegrass and roughstalk bluegrass can only be exploited in managed turfgrass systems when it does not injure the desired turfgrass. In a greenhouse study, Hoisington et al. (2014) evaluated the response of three bentgrass species, including nine creeping bentgrass varieties, velvet bentgrass, and colonial bentgrass, maintained at 1.3-cm height to different rates of sequential methiozolin applications. Hoisington et al. (2014) reported none of the creeping bentgrass varieties but both velvet bentgrass and colonial

bentgrass to be sensitive to methiozolin at rates needed to control annual bluegrass in the field. Kentucky bluegrass varietal response to methiozolin has not yet been tested. Although the response of commonly used creeping bentgrass cultivars to methiozolin is now well understood because of a study conducted by Hoisington et al. (2014) and several other peer-reviewed research on creeping bentgrass putting greens, Kentucky bluegrass varietal tolerance to methiozolin still needs to be evaluated.

The need for evaluating the response of Kentucky bluegrass to methiozolin is also important because Kentucky bluegrass is genetically similar to the weedy bluegrass species and has the potential to be injured via methiozolin applications. Kentucky bluegrass varieties have been reported to exhibit differential response to herbicides that are used for annual bluegrass control. Mueller-Warrant et al. (1997) evaluated the response of 12 Kentucky bluegrass varieties to primisulfuron and reported Kentucky bluegrass injury was affected by application date, application rate, and variety; and Kentucky bluegrass injury varied 6 to 43% among varieties. Primisulfuron at 40.5 g ha^{-1} applied in December injured Kentucky bluegrass more than the same rate applied in November or when the rate was split in half. In a different study, Affeldt et al. (2008) reported primisulfuron to injure some Kentucky bluegrass varieties more than others and reported seed yield was reduced in six of 15 varieties. Shortell et al. (2008) reported Kentucky bluegrass injury varied between 8 to 93% among 55 varieties following sequential applications of bispyribac-sodium at 188 g ha^{-1} followed by 281 g ha^{-1} , 8 weeks after initial treatment (WAIT). This variability in the response of different Kentucky bluegrass varieties to the same herbicide is attributed in part to variable ploidy levels and the unique apomictic breeding behavior of Kentucky bluegrass species (Raggi et al. 2007). The apomixes in Kentucky

bluegrass results in true-to-type seed because of reduced outcrossing that reduces recombination and fix hybrid vigor (Bashaw and Funk 1987; Bicknell and Koltunow 2004; Funk 2000; Turgeon 1999). This unique breeding behavior in Kentucky bluegrass leads to many distinct phenotypes which may vary in agronomic and morphological traits, summer stress, drought, heat, and disease tolerance (Bonos et al. 2000, 2006; Bonos and Murphy 1999; Czembor et al. 2001; Shortell et al. 2006; Wang and Huang 2004).

Methiozolin has the potential to selectively control annual and roughstalk bluegrass in Kentucky bluegrass. Although methiozolin has been found safe to some Kentucky bluegrass varieties in the US and South Korea (McNulty and Askew 2011; Koo et al. 2014), further research is needed to evaluate the impact of methiozolin over a broader spectrum of Kentucky bluegrass varieties. Therefore, research was conducted to evaluate intraspecific variability in injury, NDVI, and plant cover response between 110 Kentucky bluegrass varieties and several weeds maintained at fairway height to sequential applications of methiozolin herbicide at various rates

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Chapter 2. Methods to Measure Directional Precision of a Golf Putt: Does Annual Bluegrass Influence Ball Roll?

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ABSTRACT

Annual bluegrass (AB, *Poa annua* L.) has long been presumed to impact putting green uniformity and ball roll. However, no peer-reviewed research has evaluated the impact of AB or other putting green surface anomalies on ball roll direction. Laboratory and field research were conducted to determine the influence of AB on ball directional imprecision and bounce, and sources of error that interfere with such studies. Study results suggest that AB patches in otherwise a visibly-pure creeping bentgrass (*Agrostis stolonifera* L.) canopy can cause subtle increases in ball directional imprecision and bounce but several sources of error must be controlled before these effects can be measured. By using a mechanical putter to avoid directional errors associated with simulated-putt devices, selecting golf balls with balanced centers of gravity, eliminating legacy or "tracking" effects of repeated ball rolls via canopy brushing, and scoring ball direction 30 cm prior to the terminal acceleration, we were able to detect an increase in ball directional imprecision from 5 mm m⁻¹ when balls rolled over visibly-pure creeping bentgrass to 13 mm m⁻¹ when balls rolled over an adjacent transect that included a single patch of AB. Several laboratory and field studies were conducted to characterize the

nature of each source of error and select techniques to minimize them. For example, ball roll distance was shown to increase 3.5 cm for each subsequent ball rolled in the same track on an approximately 2.7-m putt while brushing the canopy between rolls eliminated this effect. Ball wobble while rolling on devices such as the USGA Stimpmeter®, Greenstester, and PELZmeter™ was shown to increase ball directional imprecision 28 mm m^{-1} for each $100 \text{ mm}^2 \text{ dm}^{-1}$ of on-device wobble. By measuring small differences in ball directional imprecision as influenced by greens canopy factors, future research efforts will aim to help turf managers choose appropriate greens management techniques and to evaluate performance of other devices marketed to measure greens canopy trueness.

Abbreviations: AB, annual bluegrass; CR, carpet ramp; FR, flexible ramp; GT, Greenstester; MP, Mechanical Putter; PM, PELZmeter™; SM, USGA Stimpmeter®; USGA, United States Golf Association.

Putting greens are the most time and money consuming entities on a golf course, accounting for 60 to 70% of chemical and fertilizer expenditures (Drake, 2014; Rist and Gaussoin, 1997). The putting stroke is the most common golf shot accounting for nearly half of all shots played in a round of golf (Pelz, 2000; Riccio, 1990), and considered the single most important shot that defines professional golfer's earnings (Alexander and Kern, 2005). Therefore, golf course superintendents strive for uniform and smooth greens for producing consistent putts (Drane et al., 2014). Uniformity and smoothness are among the most important components of putting green quality according to Beard (1982) in his preeminent text on golf course management.

Putting green "uniformity," however, is a largely misunderstood term. To a research agronomist, the term typically refers to consistency of texture and color of the putting green turf or to consistency of the intended turfgrass species or cultivar managed on the greens. To a golfer, the term "uniformity" implies consistency of ball roll speed and directional precision across all greens on the course. In the 1930's, Edward Stimpson invented a simple device for measuring the uniformity of ball roll speeds between greens within a golf course. In the 1970's, the United States Golf Association (USGA) conducted extensive tests on greens across the US and introduced the Stimpmeter (SM), a device based on Stimpson's original design. In subsequent years, the SM became the standard for measuring ball roll uniformity on US greens. Putting greens are said to be uniform when ball roll distance does not vary more than 15 cm between greens within a single golf course (Thomas, 1983). The SM is a simple inclined plane with a groove that guides the ball down the center from a notch that releases the golf ball when the ball-holding end is raised to approximately 20° (Anonymous, 2012a). The ball rolls down

the SM and across a reasonably level area of greens canopy, and the roll distance is recorded in feet and referred to as the "stimp" (Anonymous, 2012a).

The measurement of stimp with the SM has evolved from the original intent of ensuring uniformity of speed between greens on a given golf course to a benchmark for golfer's expectations on and between courses, a research tool to characterize the impact of turf management practices on ball roll speed, and even a job responsibility for continued superintendent employment. However, measurements with the SM are subject to inconsistencies due to variable ball release between evaluators, random ball wobble on the device, ball bounce upon ball exit, and reduced friction when subsequent balls roll in the same track (Richards et al., 2009; Pelz, 2002). In the SM user manual, the USGA indicates that the SM can lead to variability in ball roll distances, and balls deviating by more than 20 cm should be excluded from the average (Anonymous, 2012a). Several researchers have utilized the SM to evaluate the influence of greens cultural practices, such as mowing, fertility, aeration, plant growth regulators, etc., on ball roll distances. In approximately 355 measured effects of greens cultural practices on ball roll distance in peer-reviewed literature, about 55% could not be separated statistically (Donald et al., 2013; Fagerness et al., 2000; Hartwiger et al., 2001; McCullough et al., 2005a, 2005b, 2005c; McCullough et al., 2006a, 2006b; Salaiz et al., 1995) presumably due to inherent variability of the SM.

David Pelz released the PELZmeter™ (PM) in 2003 with the aim of improving consistency of green speed measurements by reducing errors associated with the SM. The PM incorporates a spirit-level system to ensure the ball is released from a consistent height, a curvilinear ramp that releases the ball horizontally onto the green to minimize ball bounce, and

three side-by-side grooves that help minimize legacy effects of previously-rolled balls (Anonymous, 2004). However, Richards et al. (2009) reported no differences between PM and SM in putting green speed measurement.

Although the objective of the golf putt is both directionally and distally dependent, it is surprising that no to very little scientific data have been published that characterize the influence of putting green surfaces on ball roll direction. Koslow and Wenos (1998) evaluated fluctuations in ball roll trueness across a green using a mechanical putting machine and reported that trueness can vary on a golf green from day to day and within the same day, depending on the time of day and traffic patterns. However, Koslow and Wenos (1998) did not assess the actual source of variation for trueness variability. Several researchers have implied that longer ball roll distances are indicative of smoother greens canopies that impart less frictional impact on ball roll behavior in general (Stahnke and Beard, 1981; Samples and Soroohan, 2008; Sweeny et al., 2000), but these claims are unsubstantiated. Moreover, there is currently no standard and quantitative method of determining putting green surface trueness (Linde et al., 2015).

Several trade magazine articles have reported visual assessment of putting green trueness using "roll" test, where a golf ball is rolled by hand across the green and visually-rated for bounce and wobble (Buchen, 1995; Linde, 2005; Windows and Bechelet, 2010). This method is far from ideal. Recently, the R&A golf organization has been promoting the "Hole Out" test whereby turf managers can use a device called the Greenstester (GT), a curvilinear incline plane, to roll golf balls repeatedly towards a putting green cup and score the number of holed balls. At a particular setting, the GT can also be used to measure ball roll distance (Anonymous, 2012b). The GT design suggests that on-device ball wobble could influence ball exit direction and

repeatedly rolling ten balls on the same line, as per Hole-Out Test protocol, could impart a massive impact on ball directional behavior as each subsequent ball tends to follow the track created by the first ball (Anonymous, 2004; Pelz, 2002). Linde et al. (2015) reported that core cultivated greens canopies with or without sand topdressing, made balls bounce and wobble on the putting green surface; however, the majority of balls still rolled in the cup following the “Hole Out” test protocol and were no different than plots that received no surface disrupting cultivation practices.

A different approach to measuring smoothness or trueness of putting green canopies utilizes devices that when rolled over the green surface, record positive, negative, and lateral G-forces of the rolling device. The Parrymeter, released in 2015, is a commercially-available device designed to transfer vertical and lateral movement of a golf ball into a platform that holds a smartphone/iPod when pushed across a green surface and generates smoothness and trueness measurement of the green (Anonymous, 2014). The Sports Turf Research Institute Trueness/Evenness Meter (STRITM) is another device that uses a metal wheel instead of a golf ball to collect the vertical and lateral deviations (Baker and Spring, 2010). This device is not available for sale but is used as a consulting tool by the inventors. McElroy et al. (2015) developed a Sphero Turf Research App that uses a robotic ball to assess surface smoothness and trueness using a similar measurement of lateral and vertical G forces. Although the Parrymeter, STRITM, and Sphero seem to evaluate trueness and smoothness of putting green surfaces, no peer-reviewed science has evaluated their performance or correlated the data they generate to ball directional precision.

The dynamics of a golf putt depend on several factors, including putting accuracy (Drane et al., 2014); golf ball construction, dimple type and dimple pattern (Bowden et al., 2010; Lemons et al., 1999; Richardson et al., 2016); environmental conditions (Streich et al., 2015; Whitlark, 2013); time of day and traffic patterns (Koslow and Wenos, 1998); and putting green surface anomalies and cultural practices (Sweeny et al. 2000; Whitlark 2013). Although much is known about the physics of a golf putt, almost all research and technological innovations to date have been related to factors that may be controlled by the golfer (Penner, 2002) or the putter design (Brouillette, 2010; Butdee and Punpojmat 2007; Drane et al., 2014; Gwyn et al., 1996; Pope et al., 2014). After the golf ball achieves "true roll", the result of the putt is governed by the surface of the putting green, environmental conditions, and other factors that are not well characterized. Although several researchers have suggested that surface anomalies on putting greens can influence ball roll behavior, most of the information is either anecdotal or comes from non-peer reviewed trade magazine articles or similar resources (Karlsen et al., 2008; Pelz, 2000; Swash, 2001). The limited peer-reviewed research that is available addresses mainly ball roll distance or speed and limited research has been conducted to evaluate the influence of surface trueness on ball roll directional precision (Koslow and Wenos, 1998). The marketing and evaluation of devices such as the GT, Parry Meter, STRITM, and Sphero indicate that there is a growing interest in evaluating putting green trueness.

We hypothesized that a putting green surface imperfection, such as infestation of weedy annual bluegrass, will increase directional imprecision of balls rolled over it. We further assumed that specialized methods would be needed to produce repeatable ball rolls that accurately reflect the influence of the greens canopy on the ball. Our objectives were 1) to assess

the influence of golf ball brand on ball center of gravity, 2) to determine the influence of ball brand and simulated-putt device on ball roll directional and distal imprecision, 3) to determine if repeatedly rolling balls on the same line will impact distal and directional imprecision and if brushing the canopy between rolls will control this potential source of error, and 4) to evaluate the influence of annual bluegrass on ball directional imprecision and bounce.

MATERIALS AND METHODS

To achieve the aforementioned objectives, six different laboratory and field trials were conducted.

Ball Center of Gravity

If a ball's center of gravity is not in the geometric center of the ball, it is called off-centered or unbalanced (Olson and Braun, 1978). Off-centered golf balls have a tendency to break to the right or left if the axis of the golf ball's center of gravity is not perpendicular to putter face at the time of impact (Olson and Braun, 1978; Pelz, 2000). A laboratory study was conducted on 19 Mar. 2014 at the Glade Road Research Facility in Blacksburg, VA to measure the influence of ball brand on ball center of gravity and to select golf balls with true center of gravity for use in subsequent laboratory and field studies.

The experiment was arranged in a completely randomized design. To encompass a wide variety of golf ball construction type, dimple designs, and dimple patterns that are used by pro and entry-level golfers, 13 ball brands or types that were available in the market were selected (Table 1). Assigning 13 different golf ball types as treatments and each ball as an experimental

unit, 12 balls from each ball brand were randomly selected and served as replications for testing center of gravity. The experiment was repeated in time. Balls were tested for center of gravity by using the methodology proposed by Olsan and Braun (1978). A floating golf ball that rapidly returns to the same resting position is off-balanced as the heavy side of the ball will spin to the bottom with each submersion. A 4.3 M sodium chloride (Morton® Salt, Morton Salt Inc., Chicago, IL 60606-1743) solution was mixed with 0.25% v/v nonionic surfactant to produce a solution to float golf balls with minimal ball-to-fluid adhesion (Olsan and Braun, 1978). The ball was submerged with a slight spinning motion and, after coming to rest, the center of the emerged ball surface was marked with an indelible marker (Sharpie Peel-off China Marker, Newell Rubbermaid, 3 Glenlake Parkway, Atlanta, GA 30328). Once marked, the ball was submerged and spun again in triplicate and both the time required for the ball to stop spinning and the resting position were recorded each time. Balls that did not return to within 30° of the original resting position were considered balanced. Data were collected for the time taken in seconds for the golf ball to come to rest and the arc length in millimeters from the initial top position. Arc length was then converted to degrees of rotation using the following formula:

$$l = \theta \cdot \frac{\pi}{180} \cdot r, \quad [1]$$

where l was the arc length in millimeters, θ was the angle in degrees made by the arc of length l at the center of circle, π was a constant with a value of 3.14, and r was the radius of golf ball in millimeters. The radius of each ball was either provided by the manufacturer or calculated mathematically.

Time to rest and rotational angle skew data were tested for normality using PROC UNIVARIATE and Shapiro-Wilk statistic in SAS (SAS Institute, 2009). Homogeneity of

variance was assessed using Levene's test on one-way ANOVAs for the main effect of golf ball brands using the HOVTEST WELCH option in the MEANS statement of PROC GLM in SAS (Welch 1951). Homogeneity of variance was further assessed by visually inspecting residuals and related diagnostics using the DIAGNOSTICS option in PROC PLOT in SAS. All data were then subjected to ANOVA using PROC GLM in SAS with sum of squares partitioned to reflect the effects of golf ball brands and their interaction with trial. Main effects of ball brand were tested using the mean square error associated with each effect's interaction with trial, which was considered random (McIntosh, 1983). Means were separated using Fisher's Protected LSD at the 5% level of significance.

Device and Ball Type Effects on Distal and Directional Imprecision of Roll

Laboratory experiments were conducted from 5 Mar. 2014 to 19 Mar. 2014 at the Glade Road Research Facility in Blacksburg, VA. A level bench made of lumber with a plywood subsurface, measuring 1.2 by 4.9 m was used to provide a leveled surface. To perfectly level the entire bench, it was covered with a self-leveling compound (LevelQuick® RS, Custom Building Products, 13001 Seal Beach Blvd., Seal Beach, CA 90740) to 1.5-cm deep. The finished surface was confirmed level to within 0.002% slope using a rotary laser level (Bosh 1000-ft Beam Self-Leveling; Bosch Packaging Services, Inc., 2240 Sumner Blvd., Raleigh, NC 27616). The finished surface was then covered with artificial putting green carpet designed for home-lawn putting greens (Challenger Industries Inc., 205 Boring Drive, PO Box 2727, Dalton, GA 30722) that measured 0.9 by 4.9 m. The putting carpet had a 6 mm tall stabilized, dual-layered, woven

100% polypropylene artificial turf with 5mm pre-coat urethane foam as a base padding and produced an 11.5-ft (3.5-m) long stimp when the surface was brushed prior to ball roll.

In order to select the most consistent ball roll technique for subsequent field experiments, we evaluated 6 ball roll devices and 13 golf ball types for consistency of ball roll distance and dispersion. Within each of 13 golf brands (Table 1), a set of three golf balls with true center of gravity, as determined by the previous laboratory experiment, were selected for each of three study repetitions. The ball roll devices used in the experiment included three commercially-available devices: USGA Stimpmeter® (SM) (United States Golf Association, 77 Liberty Corner Rd, Far Hills, NJ 07931), PELZmeter™ (PM) (Pelz Golf, Independent Golf Research, Inc., 20308 State Hwy 71 W Ste 7, Spicewood, TX 78669), and Greenstester (GT) (The Royal & Ancient Golf Club of St Andrews, St Andrews, Fife KY169JD, UK); and three custom prototypes built at Virginia Tech, including a Mechanical Putter (MP) and two devices that used curvilinear inclined planes with a flexible ramp (FR) and carpet ramp (CR) designed to reduce golf ball wobble while rolling down the ramp. The MP was built by retrofitting an electromagnetic release mechanism using an electromagnet (EM100-12-122 - 2.5 cm Diameter Round Electromagnet, APW Co., 5 Astro Place, Suite B, Rockaway, NJ 07866-4053) on a popular golf training aid (Pendulum Perfect, Performance Golf Concepts, 2349 Beverly Street, Oviedo, FL 32765).

The experiment was arranged in a randomized complete block split-plot design with 6 ball roll device main plots and 13 golf ball type sub-plots each replicated 20 times. Within each ball-roll-device main plot, the device was used to simulate a golf putt at stimp distance for each of the 13 golf ball brands, which were ordered randomly. After all 13 balls were rolled, another

ball roll device was randomly chosen, and the 13 ball brands were rolled in a different, random order. This process was repeated until each of the 13 golf balls were rolled 20 times with each of the six ball roll devices. The study was repeated three times using a unique ball for each brand in each study repetition for a total of 4680 rolls.

All device calibrations for ball roll distance and direction were conducted using the Titleist Pro V1. Each ball roll device was calibrated to propel the ball 3.5 m along the center of the putting carpet. Once the putt distance was calibrated, the device was aimed visually using a flexible string elevated slightly above the ball as a guide. The putt direction was considered calibrated when the golf ball's center did not deviate more than 1 cm from the string for 90% of the roll distance on three consecutive rolls. Preliminary observations showed that balls repeatedly rolled along the same transect tended to roll further due to the legacy left by preceding balls. To control for this phenomenon, the synthetic carpet was brushed perpendicular to the ball roll direction along the entire ball roll distance with a push broom (Quickie Bulldozer 18 in. indoor/outdoor push broom, Quickie Manufacturing, PO Box 156, Cinnaminson, NJ 08077) once between every roll.

A digital image of each ball's resting position following a targeted 3.5-m long roll was taken with a digital camera (Canon Digital Rebel XTi camera Model DS126151, Canon USA, Inc., One Canon Park, Melville, NY 11747) affixed above the ball roll bench. Images were converted to gray scale and golf ball pixels were detected using SigmaScan Pro 5 software (Systat Software, Inc., 2107 North First Street, Suite 360, San Jose, CA 95131) with intensity set at 175 to 255. The geometric center of each ball was determined by calculating the sum of all X and Y coordinates in detected pixels and dividing by the total number of pixels in each ball. The

resulting pixel coordinate was then converted to a spatial orientation using scale objects that were included in the images. The spatial resolution was 1.3 pixels mm⁻¹. Data included directional and distal imprecision of ball dispersion and total ball roll distance. Imprecision of ball dispersion was based on the deviation of each ball's resting position relative to the median position of all 20 replicates for a given ball brand by device combination.

Ball roll distance, distal imprecision, and directional imprecision data were tested for normality as previously described. All data were then subjected to ANOVA using PROC GLM in SAS with sum of squares partitioned to reflect the effects of block, ball roll device, golf ball type, ball roll device by golf ball type, and all possible interactions with trial. Main effects and interactions were tested using the mean square error associated with each effect's interaction with trial, which was considered random (McIntosh, 1983). Means were separated using Fisher's Protected LSD at the 5% level of significance.

Golf Ball Wobble Effects on Ball Direction

When golf ball dimples interact with hard surfaces, balls can roll in erratic directions. We observed that a large percentage of balls seemed to wobble or oscillate while moving down the curvilinear and linear incline planes of the GT, PM, and SM. The GT user manual suggest that dimple patterns can have a significant effect on golf ball oscillation rolling down the ramp (Anonymous, 2012b), with "large dimples" possibly magnifying this effect. However, the PM user manual claims to have eliminated this effect due to a special design of the device (Anonymous, 2004; Pelz, 2002). On-device ball wobble is believed to cause random directional changes upon ball exit. We conducted a laboratory experiment on 7 Apr. 2014 at the Glade

Road Research Facility in Blacksburg, VA to determine the influence of two ball types and four devices on ball wobble while on the device and subsequent ball direction upon exiting the device. The experiment was a randomized complete block split plot design with four ball-device main plots (SM, GT, PM, and FR) and two golf balls (Titleist Pro V1® and TopFlite Gamer®). Titleist Pro V1® was chosen because of its popularity among both golfers and researchers, and TopFlite Gamer® was chosen for its unique dimple-in-dimple pattern (Table 1).

The experiment was blocked in time and consisted of ten replications per trial and three trials. The experimental conditions and method of random main plot and split plot assignment were the same as in the aforementioned device-by-ball-type experiment but data collection differed in that the entire track of the ball was recorded both on the ramp device and after exit. A high-speed video camera (edgertronic, 300 Santana Row, Suite 200, San Jose, CA 95128) was used to record videos at $1000 \text{ frames s}^{-1}$ at a spatial resolution of $1.98 \text{ pixels mm}^{-1}$ to capture the ball's position over a 0.6-m distance equally split between on and off ramp trajectory. All devices were calibrated to approximately the same speed as the SM and ball speed ranged from 1.8 to 1.9 m s^{-1} . Each of the 240 videos were then subjected to video analysis software (Tracker 4.90, Open Source Physics) to measure the vertical and horizontal position of the ball relative to the central axis of the concerned ball roll device on approximately 350 video frames over a 0.6-m distance.

The plotted ball position was used to calculate area under the progress curve (AUPC) for ball wobble as the ball moved left or right of the central axis while on the roll device. In addition, the ball's exit direction was recorded as angle of rotation from the central axis. To control for directional skew caused by camera-to-roll-device misalignment, all positional data

were subjected to linear regression and any resulting slope was subtracted to ensure that the central axis used for assessing ball wobble and direction was aligned with the horizontal axis prior to subsequent AUPC or direction measurement. Ball wobble AUPC was expressed as $\text{mm}^2 \text{dm}^{-1}$ and ball directional angle was converted to imprecision from the central axis of the ball roll device and expressed as mm of left or right deviation m^{-1} . Ball roll wobble area and distal imprecision data were analyzed using the same procedures as in the roll-device-by-ball-type study.

Legacy Effects from Repeated Golf Ball Rolls

In previous experiments, brushing the synthetic turf canopy seemed to eliminate legacy effects of increasing ball roll distance as subsequent balls were rolled in the same track. In order to better characterize both distal and directional influence of ball roll legacy and the impact of brushing the canopy, a field study was conducted on two putting greens in Blacksburg, VA from 15 Aug. 2015 to 21 Aug. 2015. A 6-yr old putting green at the Glade Road Research Facility consisted of a 30-cm USGA-specifications (USGA 2004) root zone over native soil with subsurface drain tile. The root zone was composed of 100% sand with a pH of 6.3 and 0.8% organic matter. Creeping bentgrass cv. 'Tyee' was maintained at 3.8 mm using a walk-behind reel mower (John Deere 180B, John Deere, One John Deere Place, Moline, IL 61265). A 14-yr old putting green at the Turfgrass Research Center consisted of USGA-specification sand over a gravel intermediate layer and subsurface tile drainage. The root zone was composed of 100% sand with a pH of 6.5 and 0.5% organic matter. Creeping bentgrass cv. 'Penn A4' was maintained at 4 mm using the same walk-behind reel mower used at the Glade Road Research

Facility. Cultural practices and pest management strategies for greens at both locations were performed to mimic an in-play putting green on a golf course.

Two experiments were conducted on each of two greens to separately assess ball roll distance and direction. Each experiment was arranged in a randomized complete block design with 2 treatments, 10 replications or blocks, and 10 ball roll subsamples. Treatments for both experiments included brushing and not-brushing the putting green surface between ball rolls. The Titleist Pro V1® and MP were used for this experiment. The MP was selected due to superior performance in ball roll consistency compared to other devices in previous experiments. The MP was installed with the Nike Method Mod 00 mallet putter (Nike, Inc., 1 SW Bowerman Dr, Beaverton, Oregon 97005). The putter was designed for right-handed players and had an 89-cm long double-bend shaft attached to an oversized mallet design with 70° lie and 2.0° to-2.0° loft angle.

For the brush treatments, the putting green surface was brushed prior to every ball roll. For non-brush treatments, however, the green surface was brushed using a countertop brush (Quickie Manufacturing Corporation, PO Box 156, Cinnaminson, NJ) only before first ball roll. The MP was calibrated to putt 2.6 m long, which was equivalent to the actual stimp for both putting greens as measured using the SM. Each transect was arranged such that the slope perpendicular to ball roll direction was less than 0.1% as assessed at five equidistant locations along the transect. The slope parallel to ball roll direction was never greater than 1.3%. The MP was leveled and adjusted to a dynamic loft of 0°. The static loft of 2° reported for the Nike Method Mod putter was confirmed accurate to within 3% error using the high speed camera prior to study initiation. The golf ball was oriented in the same position for every putt and aligned

such that the geometric center of the putter face struck the geometric center of the golf ball. In the distance study, the span between the initial and final resting positions was measured for each ball.

In the ball-roll-direction study, a novel approach to measuring ball directional dispersion was invented to overcome a potential source of error first observed in laboratory studies. As the ball slows near the end of a roll, the ball's momentum is less able to overcome frictional forces imparted by the green's canopy. In approximately the last 30 cm of roll, the ball can move erratically, accounting for the majority of directional imprecision measured via ball dispersion in an uncontrolled environment. Since golfers are trained to overcome this problem by putting the ball 30 to 40 cm past the cup, an accurate assessment of ball directional imprecision should also avoid this potential source of error. To solve this problem, a strike plate was placed to intersect the ball 30-cm short of the total ball roll distance. A pressure-sensitive paper (Porelon® carbon paper, Porelon®, 1480 Gould Drive, Cookeville, TN 38506) was affixed to the strike plate and scored marks from the 10 ball-roll subsamples from a given experimental unit. Final imprecision data in mm m^{-1} were collected by measuring the deviation of each ball strike mark from the median mark in mm within a given run or replication and dividing by the roll distance.

Ball roll distance and directional imprecision data were subjected to ANOVA as described for the device-by-ball-type study. To remove variance structure from sequential putt number, ball roll distance data were regressed against sequential putt number separately for each replication, treatment, and location. The resulting slopes from each regression were subjected to ANOVA using PROC GLM in SAS with sum of squares partitioned to reflect the effects of brushing treatment, replication, location, and location by treatment. Error associated with

treatment by location was used to assess treatment main effect as indicated previously (McIntosh, 1983).

Influence of Annual Bluegrass on Directional Imprecision, Bounce, and Acceleration

The experiments were conducted from 19 June 2015 to 12 July 2015 on a total of 8 different putting greens at The Highland Golf Course, Primland Resort, Meadows of Dan, VA and The Tuckahoe Golf Course, Wintergreen Resort, Nellysford, VA. The greens at Primland Resort were USGA specification creeping bentgrass cv. 'A4' managed at 2.92 mm height to produce an average stimp of 3.35 m. At Wintergreen Resort, putting greens were USGA specification planted with a mix of 'MacKenzie' and '007' varieties of creeping bentgrass and managed at a 3.18 mm height to produce an average stimp of 3.20 m.

Putting greens on both golf courses were managed intensely and had only isolated patches of annual bluegrass covering <5% of total putting green area. Annual bluegrass patches ranged from 5 to 10 cm in diameter and had 0 to 0.5 inflorescences cm⁻². These patches were visually perceptible due to perceived differences in leaf color and texture but could not be detected by rubbing one's hand over the greens canopy. Annual bluegrass patches were randomly chosen but with the bias that each annual bluegrass patch must be surrounded by unblemished creeping bentgrass turf to allow for two adjacent ball roll transects, one rolling over the annual bluegrass patch and the other rolling only on creeping bentgrass and within 5 cm laterally. The experimental objective was to evaluate the influence of an annual bluegrass patch compared to pure creeping bentgrass on golf ball directional imprecision, bounce, and acceleration following a simulated putt from either the MP or GT. The Titleist Pro V1® was

used for this study. The MP setup and golf ball positioning methodology were the same as explained in the legacy study. The GT was leveled before each ball roll. Since the GT does not have a consistent ball roll release mechanism, the golf ball was oriented in the same fashion and gently dropped in the release hole for each ball roll in an attempt to avoid any inconsistencies.

At each of two golf course locations, the experiment was arranged as a randomized complete block split-plot design with two ball-roll-device main plots (GT and MP), two turfgrass canopy subplots (with or without annual bluegrass patch), 10 replicate blocks, and 10 subsample ball rolls per replicate. Transects were selected on both level and sloped areas of the greens. The ball roll devices were calibrated to produce 5.0-ft (1.5-m)-long putts.

Data were collected for ball directional imprecision using pressure-sensitive paper as explained in the legacy study. Ball acceleration and bounce was measured for five of the ten subsample rolls putted by the MP using the edgertronic high-speed video camera and video analysis software as previously described for the ball-wobble study. The high-speed camera was installed at ground level and oriented perpendicular to the direction of ball roll in such a way that the video frame captured 45 cm of ball roll and the ball enters the frame 15 cm from the center of the annual bluegrass patch. The videos were recorded at 1000 frames s^{-1} at a spatial resolution of 2.58 pixels mm^{-1} and average ball speed was 0.68 m s^{-1} . Ball bounce and acceleration were calculated separately for 1-dm increments before, during, and after encountering the annual bluegrass patch. Ball positional data were used to calculate the AUPC for ball bounce after removing any directional skew as discussed in the ball-wobble study. Ball acceleration was calculated as speed before, during, and after the annual bluegrass encounter and as the change in speed from before encountering annual bluegrass versus during and after encountering annual

bluegrass. Ball directional imprecision, bounce AUPC, and acceleration data were first tested for normality and equality of variance and then subjected to ANOVA and mean separation as previously described in the device-by-ball-type study with the exception that bounce and acceleration data were analyzed separately for each of four 1-dm intervals.

RESULTS AND DISCUSSION

Ball Center of Gravity

The relative center of gravity, based on ANOVA of data using methods described by Olson and Braun (1978), did not vary in rotational skew or time to rest for 13 golf ball brands that represented a range of golf ball construction type, dimple number, and dimple pattern ($P = 0.2056$ to 0.6532 , Table 1). Thus, our primary objective to select golf balls of each brand with a near true center of gravity for use in subsequent studies was easily met. From a golfer's perspective, however, one off-center golf ball can negatively impact putt performance. Mean rotational skew ranged from 65 to 109° with standard errors less than or equal to 14.2° (Table 1). Since the rotational skew of a perfectly balanced ball should be random and the average rotation of balls tested was nearly perpendicular to the starting at-float resting position of each golf ball, the data suggest that finding an out-of-balance ball among these brands would be a relatively rare occurrence. However, six golf balls out of the 156 balls tested, had a mean rotational skew of less than 30° , indicating that the balls were unbalanced.

According to mathematical models and theoretical predictions of Daemi et al. (2015), mass imbalance doesn't significantly affect the launch conditions of the ball but an unbalanced ball with off center mass of 0.2% of the ball's radius can change roll trajectory of a ball to miss a

19.0-ft (5.8-m)-long putt. To avoid possible inconsistencies in ball roll behavior arising because of off-balanced golf balls, only golf balls with true center of gravity were selected for conducting further laboratory and field trials.

Device and Ball Type Effects on Distal and Directional Imprecision of Roll

The main effect of device ($P < 0.0001$) was significant for ball directional imprecision and both trial-by-device ($P < 0.0001$) and ball-by-device ($P = 0.0497$) interactions were significant for ball distal imprecision. All other main effects or interactions were insignificant ($P > 0.05$). When averaged over trials and ball types, commercially-available ball roll devices were less precise compared to Virginia Tech custom-built prototypes. The MP and FR were the most precise devices with a directional imprecision of 4.5 and 4.8 mm m⁻¹, respectively (Table 2). The PM and SM had the greatest directional imprecision, accounting for 15.4 to 14.8 mm deviation m⁻¹ (Table 2). Thus a perfectly-aimed roll by either of these devices on uniform conditions could miss a 3.5 to 3.6-m putt based on a 54-mm golf cup radius. By comparison, the MP would require a putt distance of 12 m for a missed putt. The GT had the least directional imprecision of all commercial devices but twice the imprecision of the MP.

When trial 1 was removed from the analysis, there was no trial interaction for distal imprecision. Therefore, distal imprecision data were pooled for trials 2 and 3, and presented separately from trial 1 (Table 2). The cause of the trial interaction appears to be a change in imprecision by the FR between trial 1 and the other two trials. Possible sources of error between trials, which were repeated in time, include different personnel for brushing the synthetic turf canopy, using a different ball for each ball brand, a hand-release method, and moving to an

adjacent transect of the canopy. The actual reason for the interaction is unclear. All other devices seemed to be consistent between trials. When averaged over ball types, the SM was the most imprecise device with distal imprecision of 28.1 mm m^{-1} for trial 1 and 31.3 mm m^{-1} for trials 2 and 3 (Table 2). The FR and PM were equivalent to the least distal imprecision in both trials. According to the manufacturer, the PM was designed to overcome limitations in performance of the SM (Anonymous 2004; Pelz, 2002). Our data suggest that the PM does more precisely measure ball roll distance (Table 3) but field work by Richards et al. (2009) did not detect differences between the two devices for measuring stimp on putting greens. In the current study, all devices were perfectly leveled, balls were oriented in the same position and released in the same fashion each time, and the SM was raised using guides that kept the device straight and plumb and incorporated stops to prevent over lifting the device. We also had uniform synthetic turf with no slope. These controls may have allowed for better statistical separation between devices compared to field work.

Higher imprecision with the SM can possibly be attributed to an inconsistent ball release mechanism, random wobble of golf balls rolling down the ramp, legacy effects from repeated ball rolls on the same track of turf, and ball bounce upon ball exit from the device (Anonymous, 2004; Anonymous, 2012a; Richards et al., 2009; Pelz, 2002). The USGA has partially constrained potential SM error by recommending that users reject any ball that deviates more than 20.3 cm in distance compared to other balls in a three-ball set (Anonymous, 2012a). The distal imprecision in our study accounts for a distance plus or minus the median value. Thus, ball dispersion in our study can be calculated by multiplying the distal imprecision by the 3.5-m roll distance and doubling the value. The range of ball roll distances by the SM in our study

spans 19.7 cm, a similar value to that indicated by the USGA SM user manual (Anonymous, 2012a).

Although the interaction of ball type and device averaged over trials was significant, several factors apparently influenced ball distal imprecision, making the interaction difficult to explain. The FR was generally more consistent and had smaller distal imprecision values than some other devices across most of the balls (Table 3). This device seemed to be less subject to ball wobble than other devices and reduced on-device wobble could have led to more consistent roll distances. The SM generally produced the greatest distal imprecision for all balls and precluded the ability to discern differences between balls (Table 3). Both the TopFlite balls were among the most imprecise and Maxfli U/6, Srixon Z-Star, and Nike RZN Platinum balls were least imprecise when rolled with PM, GT, CR, and FR (Table 3). Although ball directional and distal imprecision has never been reported by any other peer-reviewed paper, Bowden et al. (2010) found no effect of golf ball type (ball construction, dimple pattern, and dimple number) and ball roll device (Stimp meter and Pelz Meter) on putting green ball roll distance. Contrary to Bowden et al. (2010), Pelz 2000 and Richardson and Gerwyn (2014) reported golf ball dimples to influence ball roll trajectory depending upon size of dimples and point of impact between putter face and part of dimple. Golf ball construction, especially dimple design and numbers are primarily aimed at improving aerodynamic properties of the ball in the air (Ting, 2003), and possibly do not have a significant effect on ball roll distance on a putting green. However, to make a successful putt on a putting green, it is important to advance the golf ball not only to a particular distance but also in a specific direction.

Golf Ball Wobble Effects on Ball Direction

Ball roll area dm^{-1} for on-device wobble and directional imprecision after exiting ball roll devices were not affected by ball type ($P \geq 0.6394$) but had a significant ball roll device effect ($P < 0.0001$). The FR had a ball-wobble area of $13 \text{ mm}^2 \text{ dm}^{-1}$, which was approximately half that of the PM and three times less than the GT and SM (Fig. 1). Similarly, directional imprecision of the FR was two to four times lower than the other devices (Fig. 1). The matching trends between devices for both ball wobble area and directional imprecision implies that a correlation could exist between the two responses. The regression of 240 responses across the three trials indicates that ball wobble area and directional imprecision are positively correlated (Fig. 2). For each $10 \text{ mm}^2 \text{ dm}^{-1}$ increase in ball wobble area, directional imprecision increases 2.8 mm m^{-1} . The highest directional imprecision measured was approximately 50 mm m^{-1} , enough to miss the cup on a 1-m putt. Our data support manufacturer's claims that the PM has reduced golf ball wobble compared to the SM reportably due to a unique grooved design (Anonymous, 2004; Pelz, 2002). In this study, directional imprecision of the PM was less than the SM in contrast to previous laboratory studies where the PM and SM had equivalent directional imprecision (Table 2). Although golf ball wobble (aka. oscillation) has often been associated with inconsistencies in SM and GT performance, there is no peer-reviewed science that reports data to support this belief. In a preliminary work, Bowden et al. (2010) reported no differences in ball roll distance as influenced by golf ball type (construction, dimple size, and dimple pattern) and ball roll device (SM and PM). However, ball roll direction as influenced by ball type and ball roll devices have not been reported by any researcher. Data from the current study suggest that on-device ball wobble can significantly influence the direction the ball takes

upon exiting the device. To avoid this potential source of error, the MP was used in subsequent field studies.

Legacy Effects from Repeated Golf Ball Rolls

Ball roll distance from a legacy of repeated ball rolls had a significant canopy brushing by sequential putt number interaction ($P < 0.0023$), but no location interaction ($P < 0.8516$). Therefore, data for ball roll distance were pooled over locations. Slopes of ball roll distances regressed against sequential putt number had a significant treatment effect ($P = 0.0474$) and no location interaction ($P = 0.3808$). Therefore, slope data were pooled over replications and locations and presented separately for each treatment. As indicated by the pooled slope of ball roll distances for each treatment, ball roll distance increased 3.4 cm with each successive putt when putting green canopy was not brushed between each sequential putt (data not shown). However, the ball roll distances changed with a slope of only -0.3 cm for each sequential putt when putting green surface canopy was brushed between each roll (data not shown). Directional imprecision was also significantly influenced by canopy brushing. When the canopy was not brushed, balls tended to remain in the track left by the first ball and directional imprecision was only 1.5 mm m^{-1} (Fig. 3). When the canopy was brushed between each ball roll, directional imprecision was 4.1 mm m^{-1} and similar to previous laboratory research when using the MP (Table 2). One of the most conspicuous design features of the PM is the three adjacent tracks that allow side-to-side rolls of three balls to overcome legacy effects associated with repeated ball rolls from the same position (Pelz, 2002). Although legacy effects have often been hypothesized to impact ball roll direction and distance, no scientific literature has tested this

hypothesis. From these studies, we determined that brushing the greens canopy between ball rolls would effectively eliminate error associated with ball roll legacy, and this practice was utilized in subsequent field studies to measure influence of annual bluegrass on ball roll direction.

Influence of Annual Bluegrass on Directional Imprecision, Bounce, and Acceleration

Ball directional imprecision had a significant canopy surface-by-ball-roll-device interaction ($P = 0.0386$) and no location interaction ($P = 0.2407$). Therefore, ball directional imprecision data were pooled across locations (Fig. 4). When the MP was used to putt balls across the greens canopy, directional imprecision increased from 5 to 13 mm m⁻¹ when the balls traversed a small patch of annual bluegrass (Fig. 4). Directional imprecision of balls rolled by the GT was independent of annual bluegrass presence and ranged from 17 to 18 mm m⁻¹ (Fig. 4). No peer-reviewed research has evaluated the impact of annual bluegrass on ball roll directional imprecision. However, Koslow and Wenows (1998), using a mechanical putter, have reported that the greatest ball roll distances and the least amount of dispersion were present in the morning hours and the days when the course was closed to play essentially because of less disturbance causing fewer surface anomalies of putting surface.

Location effects for ball bounce area were not significant ($P > 0.05$) and data were pooled over locations. When comparing balls rolled over an annual bluegrass patch to balls rolled on adjacent pure creeping bentgrass, ball bounce area was equivalent prior to encountering annual bluegrass and for the second dm after encountering the annual bluegrass (Fig. 5). When balls were rolling over annual bluegrass or for the first dm after encountering annual bluegrass, ball

bounce area increased approximately 5 to 9 mm² dm⁻¹ (Fig. 5). Thus, the annual bluegrass patch increased ball bounce area 26 to 36% compared to balls rolling on adjacent pure creeping bentgrass. Increased ball bounce could conceivably increase frictional influence of the greens canopy on ball direction. No peer-reviewed research has evaluated or estimated the impact of annual bluegrass or other putting green surface anomaly on ball bounce.

Acceleration changes between balls rolled over an annual bluegrass patch compared to adjacent pure creeping bentgrass could not be statistically separated (data not shown). At 20 replicates spanning two trial locations, average slope perpendicular to the direction of ball travel was 4.1% with a 2.5% standard deviation and average slope in the direction of ball travel was 0.9% with a standard deviation of 2.3% (data not shown). The influence of slope could have hindered efforts to discern differences in ball acceleration caused by annual bluegrass. Rist et al. (1999) developed a system to measure ball acceleration through a tube containing photoelectric switches. Although they could not detect differences in ball roll distance, significant differences in ball acceleration were referenced between rolling the ball with or against the mowing direction and between the numbers of time mowed. The authors concluded that a significant difference in ball acceleration between mowing factors was attributed to greens canopy characteristics having influence on the ball, but potentially significant sources of error, such as using the SM to roll balls, were not considered. It is hard to compare the current study to results obtained by Rist et al. (1999). In the current study, ball acceleration was measured approximately 437 times in a 30-cm span and a total of 50 balls were rolled for each treatment effect. In the Rist et al. (1999) study, ball acceleration was measured five times in a 76-cm span and only three balls were rolled for each treatment effect.

The majority of research to date has reported how greens management techniques, such as mowing and chemical treatments, can influence ball roll distance (Fagerness et al., 2000; Johnson et al., 2003; McCullough et al., 2005a, 2005b, 2005c; McCullough et al., 2006a, 2006b; McDonald et al., 2013). To our knowledge, there aren't any peer-reviewed papers that report data on how site-specific canopy anomalies or whole-green management inputs, except Koslow and Wenos (1998), affect ball roll direction. Results of these studies suggest that measuring subtle influences on ball directional imprecision as influenced by the greens canopy surface is possible, but several sources of error must be minimized. Current commercially-available resources either are not capable of separating the impact of greens canopy anomalies on ball directional imprecision or have not been subjected to scientific research for that purpose. Future research will leverage the techniques developed in the current study to measure the degree of correlation between data generated by new technologies for measuring green trueness (ParryMeter and Sphero Turf Research App) and ball directional imprecision.

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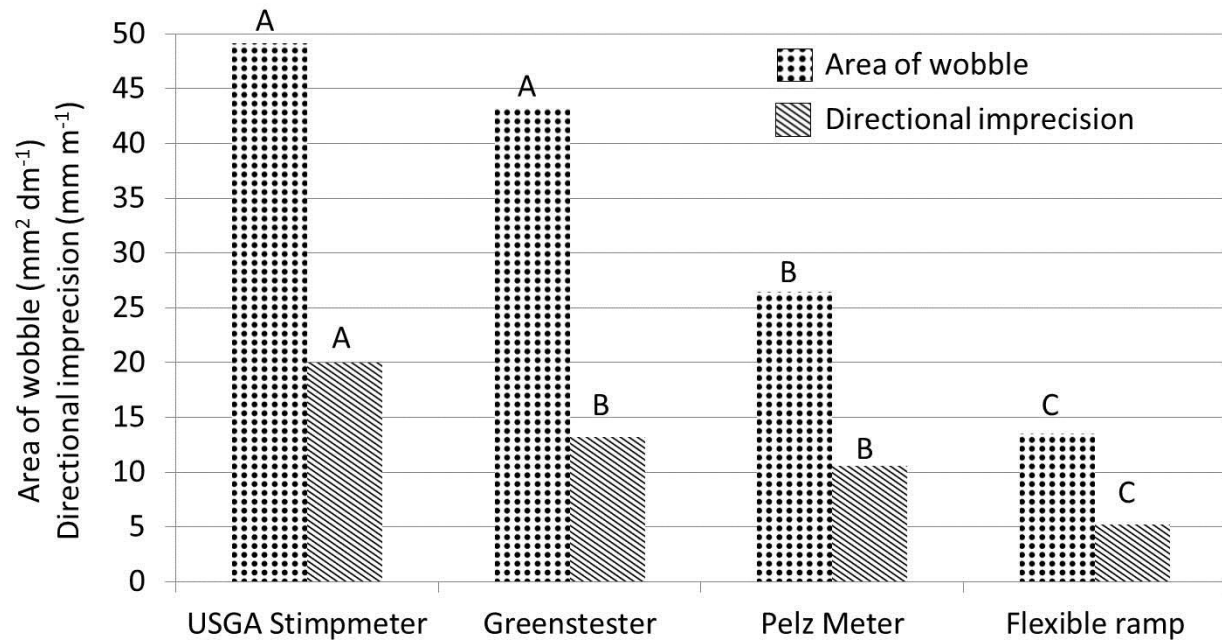


Fig. 1. Influence of ball roll device on area of on-device wobble and directional imprecision of golf ball upon exiting device in laboratory studies conducted on a simulated putting green surface at the Glade Road Research Facility in Blacksburg, VA. Uppercase letters within the response variable separate mean area of wobble and directional imprecision according to the Fisher's protected LSD at 5% level of significance.

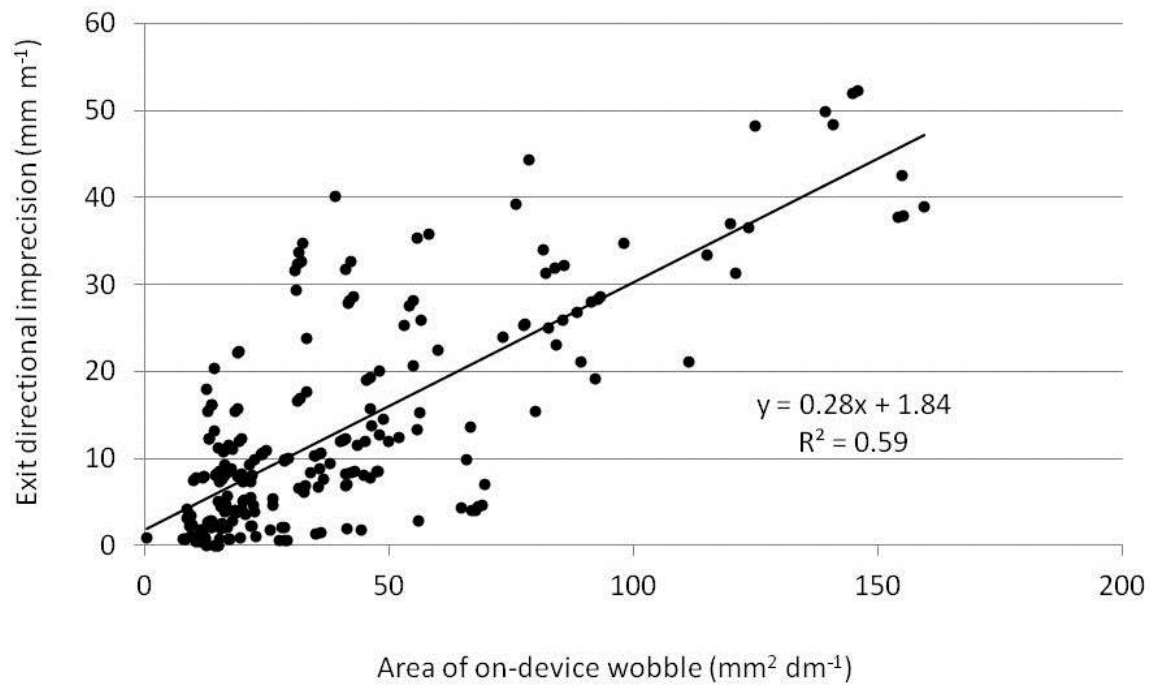


Fig. 2. Regression of on-device wobble area with ball directional imprecision based on digital analysis of ball position at approximately 1.7-mm increments over a 0.6-m distance that was equally split between ball roll on device and after exiting the device, including four devices (USGA Stimp Meter, PELZmeter™, Greenstester, and a Virginia Tech Flexible Ramp Prototype), two ball types (Titleist Pro V1, and TopFlite Gamer), and three trials.

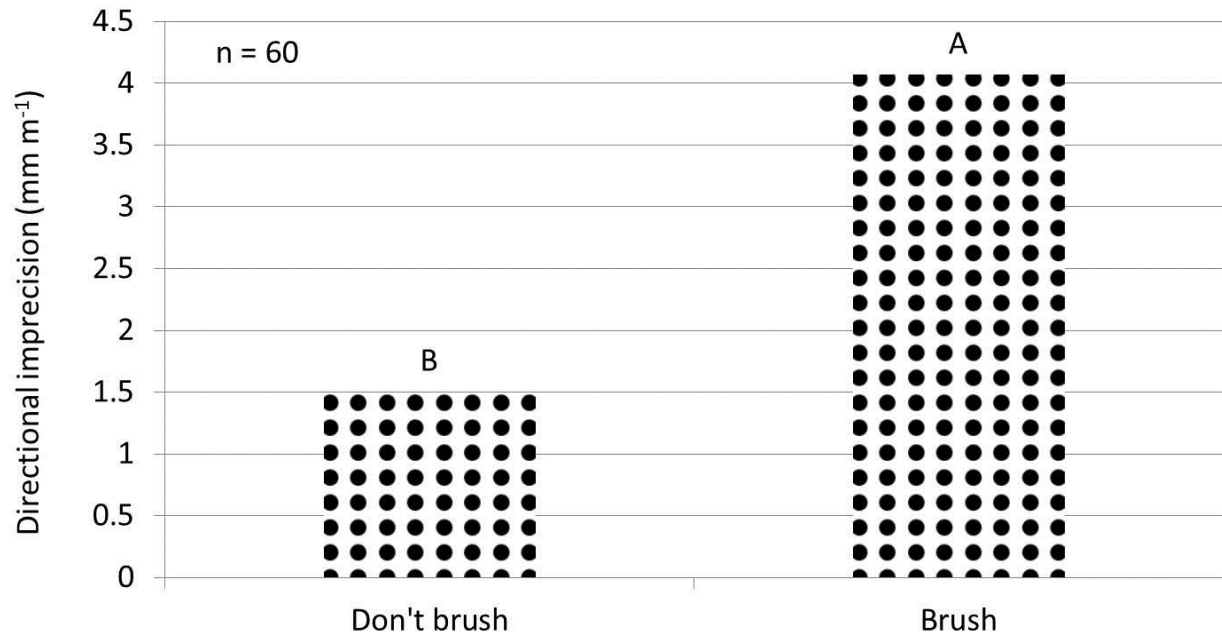


Fig. 3. Effect of brushing putting green canopy between consecutive ball rolls on directional imprecision of ball roll in the field studies conducted at the Glade Road Research Facility and Turfgrass Research Center in Blacksburg, VA. Directional imprecision data were averaged over two locations. Uppercase letters within the putting surface canopy treatment separate mean directional imprecision data according to the Fisher's protected LSD at 5% level of significance.

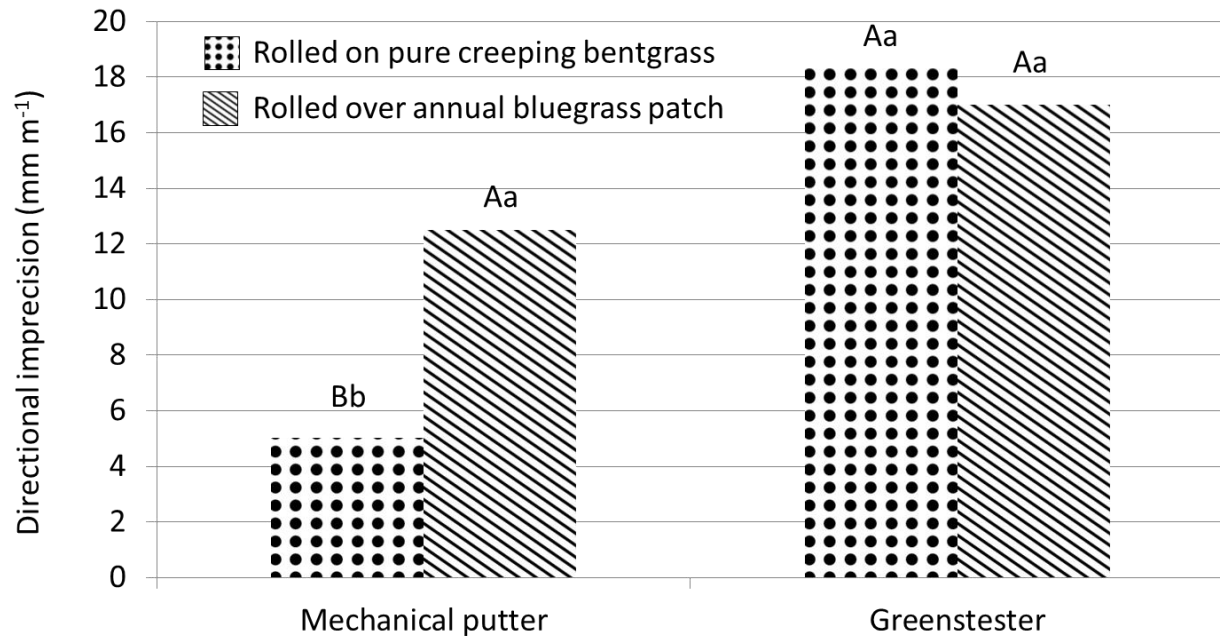


Fig. 4. Effect of putting surface canopy surface interface on ball roll directional imprecision when comparing a visually-pure creeping bentgrass (*Agrostis stolonifera* L.) area to an area with a visually-identified patch of annual bluegrass (*Poa annua* L.) in field studies conducted at the Primland and Wintergreen Resorts in Meadows of Dan and Nellysford, VA, respectively. Data were pooled over locations ($P > 0.05$). Uppercase and lowercase letters separate mean directional imprecision within plant species and ball roll devices, respectively, according to the Fisher's protected LSD at 5% level of significance.

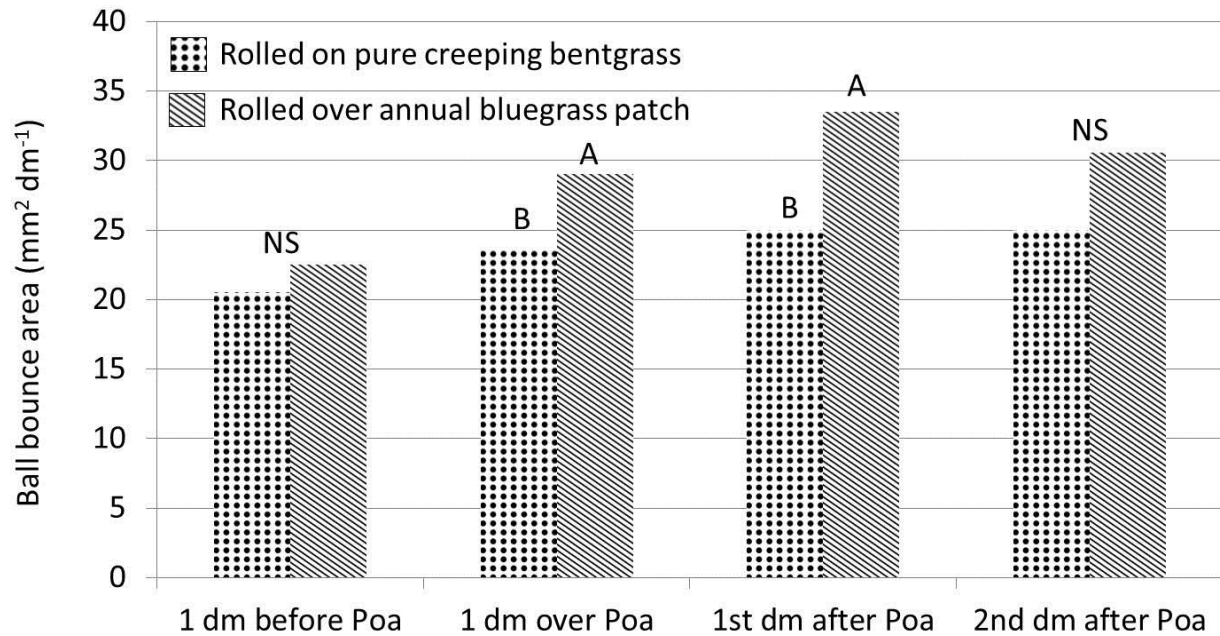


Fig. 5. Effect of putting surface canopy surface interface on ball bounce at four independent 1-dm intervals with respect to an annual bluegrass (*Poa annua* L.) or *Poa* patch over a 5.0-ft (1.5-m)-long putt in the field studies conducted on creeping bentgrass (*Agrostis stolonifera* L.) putting greens at the Primland and Wintergreen Resorts in Meadows of Dan and Nellysford, VA, respectively. Data were pooled over locations ($P > 0.05$). Uppercase letters within the response variable separate mean directional imprecision according to the Fisher's protected LSD at 5% level of significance. NS = not significant.

Table 1. Classification of golf balls used in laboratory and field studies and descriptive statistics of rotation angle, time to rest, and number of unbalanced balls based on floating balls in a sodium chloride solution to test relative center of gravity (Olsan and Braun, 1978) where a rotation angle of less than 30° is considered unbalanced.

Golf ball brand and model	Construction [†]	Dimple design [‡]	Dimples ball ^{-1†}	Rotation angle (°± SE)	Time to rest (s ±SE)	No. unbalanced balls
Callaway Hex Warbird®	2P-SC-1c	Hexagonal	332	77.6 (7.40)	6.24 (0.16)	1
Callaway Speed Regime 3	5P-SC-3c	Hexagonal	332	90.4 (10.2)	5.82 (0.26)	0
Maxfli® U/6	O-SC-1c	Triangle in sphere	336	93.3 (10.4)	6.11 (0.15)	0
Nike RZN Platinum	4P-SC-2c	Spherical	360	87.4 (11.7)	6.03 (0.20)	1
Nike Vapor Black 2.0	2P-SC-1c	Spherical	314	96.0 (8.67)	6.25 (0.17)	0
Srixon® Soft Feel	2P-SC-1c	Spherical	324	86.0 (9.30)	6.38 (0.27)	1
Srixon® Z-Star	3P-SC-1c	Spherical	344	105 (11.4)	5.44 (0.15)	1
TaylorMade® Noodle	2P-SC-1c	Spherical	342	84.6 (9.36)	5.56 (0.16)	0
TaylorMade® TPX	5P-SC-2c	Spherical	322	87.4 (11.9)	6.47 (0.26)	1
Titleist® NXT Tour S	2P-1c	Spherical	302	83.2 (7.05)	4.84 (0.15)	0
Titleist® ProV1	3P-1c	Spherical	352	65.4 (6.24)	5.55 (0.32)	1
Top-Flite® Gamer	3P-SC-2c	Sphere in sphere	332	89.6 (14.2)	5.68 (0.22)	0
Top-Flite® XL Distance	2P-SC-1c	Spherical	332	109 (10.0)	5.68 (0.31)	0

[†] 1c, single cover; 2c, double cover, 2P, two-piece; 3P, three-piece; 4P, four-piece; 5P, five-piece; O, other; SC, solid center.

Information about golf ball construction type and dimple numbers ball⁻¹ was inherited from USGA's monthly publication -

Conforming golf balls (Anonymous, 2016).

‡ Dimple design and pattern information was either collected from the individual manufacturer or by personally observing balls from each of the 13 brands used in the study. Regardless of dimple numbers, design, and patterns, all golf balls have different sized dimples interspersed on the ball surface in a specific design.

Table 2. Influence of ball roll device on directional and distal imprecision of golf ball's resting position in a laboratory study conducted at the Glade Road Research Facility, Blacksburg, VA.

Ball roll device	Directional imprecision†	Distal imprecision†	
		Trial 1	Trials 2 and 3
		mm m ⁻¹	
Mechanical putter	4.5d‡,§	19.6b‡,§	19.6c‡,§
Flexible ramp	4.8d	19.0b	15.4d
Carpet ramp	7.6c	18.6b	23.9b
Greenstester	9.2b	18.1b	20.5c
USGA Stimpmeter®	15.4a	28.1a	31.3a
PELZmeter™	14.8a	16.9b	18.2cd

† Directional imprecision was determined by first calculating lateral deviation using pixel coordinates of each golf ball's resting position relative to pixel coordinates of aiming line of the putt in the digital image, and then, calculating lateral deviation of each golf ball's resting position from the median resting position of all the ball rolls within each of 13 golf ball types.

Distal imprecision was determined by first calculating ball roll distances using total distance between the putter head and initiation of camera view for digital images, and pixel coordinates of golf ball's resting position in a digital image. Ball roll distances were then used to calculate deviation in distance of each golf ball's resting position from the median resting position of all the ball rolls within each of 13 golf ball types.

‡ Directional imprecision had no trial-by-device interaction ($P > 0.05$); therefore, data were pooled over trials. Distal imprecision had a significant trial-by-device interaction ($P < 0.0001$); however, trial interaction was not significant when trial 1 was removed from analysis ($P = 0.1942$). Therefore, distal imprecision data is presented separately for trial 1, and pooled for trials 2 and 3.

§ Means within a column followed by the same letter do not significantly differ according to the Fisher's Protected LSD test at $P \leq 0.05$.

Table 3. Influence of ball roll device and ball type on distal imprecision in a laboratory study conducted at the Glade Road Research Facility, Blacksburg, VA.

	Distal imprecision†						
	Mechanical putter	Flexible ramp	Carpet ramp	USGA Stimpmeter	PELZmeter	Greenstester	LSD‡
	mm m ⁻¹						
Callaway Hex Warbird®	14.2	16.3	29.3	34.2	18.9	19.0	8.8
Callway Speed Regime 3	18.6	15.2	19.9	35.5	14.9	17.1	7.4
Maxfli® U/6	21.3	11.5	32.9	32.9	17.3	19.8	9.1
Nike RZN Platinum	18.7	16.9	25.6	31.2	21.3	22.0	8.2
Nike Vapor Black 2.0	24.3	12.5	18.0	31.9	19.0	14.0	9.0
Srixon® Soft Feel	17.3	16.1	22.2	30.3	21.4	23.1	8.4
Srixon® Z-Star	18.4	12.8	17.1	25.8	14.9	16.0	6.3
TaylorMade® Noodle	19.9	14.7	23.8	33.8	23.1	24.6	8.8
TaylorMade® TPX	25.8	15.2	11.7	27.2	19.0	15.6	7.4
Titleist® NXT Tour S	20.2	16.7	30.1	33.2	16.5	26.0	8.4
Titleist® ProV1	19.6	14.1	23.3	36.5	12.6	23.6	9.0
Top-Flite® Gamer	19.4	22.0	32.1	29.1	20.7	23.2	9.7
Top-Flite® XL Distance	17.2	15.7	25.4	25.9	17.3	22.6	8.4
LSD‡	6.8	6.1	10.1	10.5	6.6	7.8	

† LSD, least significant difference at $\alpha = 0.05$

‡ Distal imprecision was determined by first calculating ball roll distances using total distance between the putter head and initiation of camera view for digital images, and pixel coordinates of golf ball's resting position in a digital image. Ball roll distances were then used to calculate deviation in distance of each golf ball's resting position from the median resting position of all the ball rolls within

each of 13 golf ball types. Distal imprecision had a significant device-by-ball interaction ($P \leq 0.05$) and no trial interaction ($P = 0.2232$). Therefore, distal imprecision data are presented as pooled over trials and separately for devices and ball types.

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Chapter 3. Long-Term Annual Bluegrass and Roughstalk Bluegrass Control in Cool-Season Turfgrass Fairways

Sandeep S. Rana and Shawn D. Askew *

Methiozolin is a new isoxazoline herbicide that has been found promising to selectively control annual bluegrass and roughstalk bluegrass in cool-season turf. However, most peer-reviewed research to date is limited only to evaluating methiozolin for annual bluegrass control on putting greens. Field trials were conducted with objectives of comparing various application regimes of methiozolin for long-term roughstalk bluegrass and annual bluegrass control in cool-season golf fairways. Two trials each on creeping bentgrass golf fairways and Kentucky bluegrass research fairway were conducted. Treatments consisted of methiozolin at 1000 or 1500 g ai ha⁻¹ applied four times in fall or spring or twice in fall fb twice spring; methiozolin at 1000 g ha⁻¹ applied twice in fall fb by methiozolin plus primisulfuron (26.3 g ha⁻¹) or amicarbazone (98 g ha⁻¹) applied twice in spring; primisulfuron or amicarbazone applied twice in spring; and bispyribac-sodium at 24.7 g ha⁻¹ (only on creeping bentgrass sites) applied twice in fall fb twice in spring. Treatments also included a non-treated check for comparison. All treatments were applied at two-wk intervals within the season and were repeated the following yr for a two-yr application program. Methiozolin-only treatments did not injure creeping bentgrass or Kentucky bluegrass,

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reduce quality, or reduce normalized difference vegetative index regardless of application timings and rates. Only primisulfuron- and bispyribac-sodium-containing treatments injured desirable turfgrass. In general, fall applications of methiozolin reduced roughstalk bluegrass and annual bluegrass cover more than the spring-only treatments. At 1 yr after last treatment (YALT), methiozolin at 1500 g ha⁻¹ applied four times in fall for two consecutive yr reduced roughstalk bluegrass and annual bluegrass cover $\geq 85\%$ and more consistently and effectively than other treatments. When methiozolin was applied all in spring or split between fall and spring, generally methiozolin at 1500 g ha⁻¹ reduced roughstalk bluegrass better than methiozolin at 1000 g ha⁻¹. Amicarbazone and primisulfuron applied alone did not reduce annual and roughstalk bluegrass cover compared to the non-treated check, 1 YALT. Bispyribac-sodium reduced roughstalk bluegrass inconsistently among trials and better efficacy of bispyribac-sodium on roughstalk bluegrass came at the expense of increased creeping bentgrass injury. Results of this study suggest that methiozolin at 1500 g ha⁻¹ applied four times in fall at 2-wk intervals for two consecutive yr controls roughstalk bluegrass and annual bluegrass better and more consistent than other herbicides or treatment regimes.

Nomenclature: Methiozolin, 5-(2,6-difluorobenzyl)oxymethyl-5-methyl-3-(3-methylthiophen-2-yl)-1,2-isoxazoline, code names: EK-5229, SJK-03, and MRC-01; annual bluegrass, *Poa annua* L.; roughstalk bluegrass, *Poa trivialis* L.; creeping bentgrass, *Agrostis stolonifera* L.; Kentucky bluegrass, *Poa pratensis* L.

Keywords: Annual bluegrass control, grid count, NDVI, roughstalk bluegrass control, turfgrass injury, turfgrass quality.

Roughstalk bluegrass (*Poa trivialis* L.) is a perennial grass weed that spreads by stolons and rarely produces seedheads in managed turf (Beard 1973; Reicher et al. 2006). Both annual bluegrass (*Poa annua* L.) and roughstalk bluegrass are considered weeds primarily due to differences in leaf color and density compared to turfgrasses such as Kentucky bluegrass, perennial ryegrass, tall fescue, and creeping bentgrass. Although both species can be weedy in most turfgrass situations, roughstalk bluegrass is more problematic in higher cut turf (lawns, fairways, athletic fields) and annual bluegrass is most problematic on golf putting greens (Bell et al. 1999). During spring and fall, both annual bluegrass and roughstalk bluegrass can outgrow major cool-season turfgrasses but are subject to stress-related injury during hot summers and cold winters resulting in poor aesthetics and increased management costs (Carrow and Duncan 1998; Christians 2004). Control of both these weedy bluegrass species is important to maintain aesthetics and functionality of desirable turf; however, selective control options for annual bluegrass and roughstalk bluegrass are limited in cool-season turfgrasses such as Kentucky bluegrass and creeping bentgrass.

Although cultural practices and plant growth regulators can be used to suppress annual bluegrass and roughstalk bluegrass (Aldahir et al. 2015; Haguewood et al. 2013; Thompson et al. 2016), effective and long-term control relies primarily on selective herbicides. Postemergence roughstalk bluegrass control in the cool-season turf is limited to spot treatment with nonselective herbicides, like glyphosate, followed by reseeding with desired turfgrass (Liskey 1999; Morton et al. 2007). Mueller-Warrant (1990) reported late-winter to late-spring applications of fenoxaprop to control roughstalk bluegrass in perennial ryegrass but the efficacy varied among seasons with poor performance from applications made before winters. Moreover, better

roughstalk bluegrass control with late-spring applications came at the expense of increased injury to perennial ryegrass (Mueller-Warrant 1990). Additionally, rates of fenoxaprop needed to control roughstalk bluegrass are too injurious to creeping bentgrass; thereby, limiting use on golf courses (Anonymous 2011a).

Morton et al. (2007) evaluated bispyribac-sodium and sulfosulfuron for roughstalk bluegrass control in creeping bentgrass but because of differences in cultivar sensitivity, application timings, and temperatures across yr and locations, turf and weed response were variable and not conclusive enough to recommend a single best strategy. The dependency of bispyribac-sodium and sulfosulfuron efficacy on temperature, with better performance under warmer temperatures, has also been reported by other researchers (Lycan and Hart 2006; McCullough and Hart 2006). Thompson et al. (2016) evaluated bispyribac-sodium, paclobutrazol, and tank-mixtures of amicarbazone and mesotrione for roughstalk bluegrass control, and reported that only bispyribac-sodium effectively controlled roughstalk bluegrass. Summer applications of bispyribac-sodium at 74 g ha^{-1} applied three times at 2-wk intervals controlled roughstalk bluegrass 14 to 90% depending on location when assessed 3 to 4 months after initial treatment (Thompson et al. 2016). In lawn-height (7.6 cm) turf, McNulty and Askeew (2011) reported 90% roughstalk bluegrass control with sequential applications of bispyribac-sodium at 74 g ai ha^{-1} at 4 wk after treatment (WAT) but no control was evident one yr later.

Primisulfuron, a sulfonylurea herbicide not labeled for use in turf, at 26.3 g ha^{-1} has been reported to control roughstalk bluegrass 83% at 3 WAT (Post et al. 2013). Amicarbazone is a newer herbicide for annual and roughstalk bluegrass that has also been reported by Landry et al. (2011) to control weedy bluegrass species 70% and better than bispyribac-sodium and

sulfosulfuron. However, amicarbazone at 0.5 kg ha⁻¹ injured creeping bentgrass 65% and reduced stand density 45%, 3 WAT. By 6 WAT, turf injury was less than 20% from all three rates of amicarbazone used in the experiment (Landry et al. 2011).

Postemergence annual bluegrass control options in cool-season turf are limited to bispyribac-sodium, ethofumesate, amicarbazone, and tenacity. Bispyribac-sodium produces inconsistent turf safety and annual bluegrass control due to seasonal variability in application timing and temperature (Hart and McCullough 2007; Lycan and Hart 2006; McCullough and Hart 2006). McNulty and Askew (2011) reported bispyribac-sodium to injure Kentucky bluegrass 60% 9 d after treatment (DAT) and control annual bluegrass less than 40% by 7 WAT. McCullough and Hart (2006) also reported temperature to significantly influence bispyribac-sodium safety to creeping bentgrass and efficacy to control annual bluegrass with better control and minimal injury at warmer temperatures of 20 to 30 C but an opposite response at 10 C. Bispyribac-sodium also causes significant injury to Kentucky bluegrass under traffic and shade (Anonymous 2010).

Ethofumesate has also been reported to control annual bluegrass postemergence by causing irreversible cell division abnormalities (Haggard and Passman 1981; Jukes and Goode 1981; Lee 1977; Lee 1981; Shearman 1986; Woosley et al. 2003). However, researchers have found conflicting results for efficacy of ethofumesate in controlling annual bluegrass with safety to desired cool-season turf. Lee (1981) reported ethofumesate at 1.1 kg ha⁻¹, a rate lower than that needed for annual bluegrass control (Jukes and Goodes 1981), to eliminate stand counts of several cool-season turfgrasses. Mesotrione is also reported to control annual bluegrass PRE or POST (Anonymous 2011b; Askew et al. 2003). Branham et al. (2010) and Skelton et al. (2012)

have reported frequent and sequential applications of mesotrione at 0.11 kg ha⁻¹ or lower to control annual bluegrass up to 95%. However, Richer et al. (2011) noted erratic annual bluegrass control from the sequential application of mesotrione at 0.28 and 0.39 kg ha⁻¹ at two locations.

Methiozolin is a new isoxazoline herbicide being developed by Moghu Research Center (Yuseong, Daejeon, Korea) primarily for controlling annual bluegrass on putting greens (Koo et al. 2014). Research suggests that methiozolin at 500 to 1000 g ha⁻¹ applied two to five times per yr can control annual bluegrass POST on creeping bentgrass greens and new seedling annual bluegrass populations can be prevented with methiozolin at 500 g ha⁻¹ applied once each in spring and fall (Askew and McNulty 2014; Brosnan et al. 2013; McCullough et al. 2013; Koo et al. 2014). Researchers in South Korea (Hong and Tae 2013; Koo et al. 2014) and the United States (Askew and McNulty 2014; McCullough et al. 2013) have reported methiozolin safety to all major cool- and warm-season turfgrasses.

Although little is known about methiozolin efficacy for annual bluegrass and roughstalk bluegrass control in fairway-height turf, previous research at Virginia Tech (United States) and in South Korea has reported methiozolin to control both the weedy bluegrass species in fairway-height turf at rates at least twice (1000 g ha⁻¹) that needed on putting greens (McNulty and Askew 2011). At Pine Ridge Country Club in South Korea, methiozolin at 1000 g ha⁻¹ applied thrice in fall and spring controlled roughstalk bluegrass over 90% without injuring Kentucky bluegrass over a period of three yr (SJ Koo, personal communication). Post et al. (2013) reported methiozolin tank-mixed with primisulfuron as an effective in-season control option for annual bluegrass and roughstalk bluegrass control. Sequential applications of methiozolin at

1000 g ha⁻¹ plus primisulfuron at 26.3 g ha⁻¹ and methiozolin at 2000 plus primisulfuron at 13.1 and 26.3 g ha⁻¹ controlled annual bluegrass 88 to 98% at 7 wk after initial treatment (WAIT) (Post et al. 2013).

Limited research is available on application timing and rates of methiozolin alone or methiozolin tank-mixed with currently available herbicides for long-term control of these weedy *Poa* species in Kentucky bluegrass and creeping bentgrass turf managed at heights typical of golf fairways or athletic fields (approximately 1.5 cm). Therefore, field trials were conducted with the objective of evaluating creeping bentgrass and Kentucky bluegrass injury, cover, and normalized difference vegetative index (NDVI); annual bluegrass and roughstalk bluegrass control, cover, and NDVI; and turf NDVI and quality following methiozolin applications at several different timings and tank-mixtures.

MATERIALS AND METHODS

Trials were initiated on October 22, 2013 (GR1) and October 21, 2014 (GR2) on a Kentucky bluegrass research fairway at the Glade Road Research Facility in Blacksburg, VA and on October 22, 2013 on separate creeping bentgrass fairways at the Pete Dye River Course of Virginia Tech (PDRC) in Radford, VA and the Highland Course of Primland Resort (HCPR) in Meadows of Dan, VA. The research fairway at the Glade Road Research Facility had ‘Midnight II’ Kentucky bluegrass and creeping bentgrass at both HCPR and PDRC was ‘L-93.’

The Kentucky bluegrass fairway for GR1 and GR2 was maintained at 15 mm using a John Deere 7500A PrecisionCut™ Fairway Mower (John Deere, One John Deere Place, Moline, IL 61265) and had a pH of 6.9 and 2.7% organic matter. This fairway received 170 kg N ha⁻¹

annually. The creeping bentgrass fairway at HCPR was maintained at 10 mm using a Toro Reelmaster 5410 (The Toro Company, 8111 Lyndale Avenue S, Bloomington, MN 55420) and had a pH of 6.2 and 6% organic matter. The fairway was core aerated with a John Deere 1500 aerifier (John Deere, One John Deere Place, Moline, IL 61265) installed with 2.22-cm-diameter tines in March and 1.59-cm-diameter solid tines in June and November. Additional topdressing operations were performed in March, September, and November. The fairway was also verticut in March using a Wiedenman Verticutter (Wiedenman North America, LLC, 25 Telfair Pl, Savannah, GA 31415). In addition, the fairway received 145 kg N ha⁻¹ and 196 kg K ha⁻¹ per yr. Lime was applied either as dolomitic or calcitic or gypsum depending on soil test reports. The creeping bentgrass fairway at PDRC was maintained between a range of 13 and 17 mm and had a pH of 6.5 and 6% organic matter. Although cultural practices and fertilizer programs followed at PDRC were similar to HCPR, the overall intensity of turfgrass management operations at PDRC was much lower.

At GR1 and GR2, winter annual broadleaf weeds and grasses were allowed to germinate and grow in spring to evaluate the efficacy of herbicides programs used in this study on species other than annual bluegrass and roughstalk bluegrass. After last spring evaluation, all broadleaves were controlled using a four-way product containing carfentrazone, 2,4-D, mecoprop, and dicamba (Speedzone® herbicide, PBI Gordon Corporation, 1217 West 12th Street, Kansas City, MO 64101) at 1.5 kg ae ha⁻¹, goosegrass was controlled using topremazone (Pylex™ herbicide, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709) at 49 g ae ha⁻¹, and crabgrass was controlled using quinclorac (Drive® XLR8 herbicide, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709) at 1.7 kg ae ha⁻¹.

The experiments at each location were arranged in a randomized complete block design with three replications. Treatments consisted of methiozolin at 1000 or 1500 g ai ha⁻¹ applied four times in fall or spring or twice in fall fb twice in spring; methiozolin at 1000 g ha⁻¹ applied twice in fall fb by methiozolin plus primisulfuron (26.3 g ha⁻¹) or amicarbazone (98 g ha⁻¹) applied twice in spring; primisulfuron or amicarbazone applied twice in spring; and bispyribac-sodium at 24.7 g ha⁻¹ (only on creeping bentgrass sites) applied twice in fall fb twice in spring. A nontreated check was included for comparison. All treatments were applied at two-wk intervals within a given season and the treatment programs were implemented both spring and fall for two consecutive years. All treatments were applied with a CO₂-pressurized backpack sprayer equipped with TTI11004 nozzles (Teejet Technologies, Springfield, IL 62703), which delivered 281 L ha⁻¹ of spray solution at 290 kPa. For times when only methiozolin was applied, trials were irrigated immediately following applications to promote the activity of methiozolin which is dependent on root uptake and acropetal mobility (Koo et al. 2014). When methiozolin was applied in conjunction with other herbicides, trials were irrigated within 24 hr following application.

Data were collected from at least two sites at biweekly intervals in fall and spring or when weeds of interest were present. Data collected included visually-estimated and line-intersect cover and visually-estimated injury/control for creeping bentgrass, Kentucky bluegrass, roughstalk bluegrass, annual bluegrass, smooth crabgrass, common chickweed, and Persian speedwell. Visual estimations of injury and control were made on a 0 to 100% scale based on a reduction in apparently healthy, green tissue compared to the nontreated areas where 0 was no injury, 30% was maximum acceptable injury, and 100% was a complete loss of all green tissue

in plots and apparent death of plants (Frans et al. 1986). Since both roughstalk bluegrass and annual bluegrass become more conspicuous in spring, line-intersect data were also collected on the entire plot at 81 intersects m^{-2} for creeping bentgrass, Kentucky bluegrass, annual bluegrass, and roughstalk bluegrass in each of the three spring seasons during the trial duration.

Overall turf quality data were assessed at each rating date on a 1 to 9 scale, where 9 is ideal turf quality, 6 is minimally acceptable turf quality, and 1 is a complete loss of green turf. Turf NDVI was collected at all rating dates using a multispectral analyzer (Crop Circle™ Model ACS-210, Holland Scientific Inc., 6001 South 58th Street, Lincoln, NE 68516). In addition to whole-plot assessment, NDVI data were also collected separately for desired turfgrass and roughstalk bluegrass at each rating date. Separate NDVI ratings for different species were collected using a Spectral Evolution PSR-1100 spectroradiometer (Spectral Evolution, 1 Canal St, Lawrence, MA 01840).

The average response of 15 to 23 evaluation dates, depending on response variable, over the 2.5-yr trial duration and the final response at 1 YALT were analyzed separately for each response. Data for each response variable were tested for normality using PROC UNIVARIATE and Shapiro-Wilk statistic in SAS software (version 9.2, SAS Institute, 100 SAS Campus Drive, Cary, NC 27513-2414) and homogeneity of variance was confirmed by visually inspecting plotted residuals and other metrics using the DIAGNOSTIC option in PROC PLOT of SAS. Homogeneity of variance was further assessed using Levene's test where one-way ANOVAs for main effects or all possible combinations of factorial levels were tested using the HOVTEST WELCH option in the MEANS statement of PROC GLM in SAS. When needed, data were transformed to the log or arcsin square root to meet assumptions of ANOVA. In such cases

where transformation was needed, data were back transformed for presentation clarity. All measured responses were subjected to a combined ANOVA using PROC GLM in SAS with the sum of squares partitioned to reflect the effects of block; and also a trial, herbicide program, and their interactions. Main effects and interactions were tested using mean square error associated with the random variable interaction (McIntosh 1983). Appropriate means were separated with Fisher's Protected LSD at 5% level of significance. To test the correlation of visually estimated plant cover with cover evaluated using line-intersect method, plant cover data at 1 YALT were also subjected to PROC CORR in SAS software to determine the Pearson's correlation coefficient among the two plant cover assessment techniques used in the study.

RESULTS AND DISCUSSION

Kentucky Bluegrass Trials. Kentucky bluegrass average cover and injury had a significant treatment effect ($P < 0.05$) but no trial-by-treatment interaction ($P > 0.05$); therefore, Kentucky bluegrass cover and injury data were pooled over trials (Tables 1 and 2). All treatments containing fall applications of methiozolin maintained Kentucky bluegrass cover $\geq 60\%$, which was 1.4 times that of the nontreated check, and greater than other treatments (Table 1). Kentucky bluegrass average cover following spring applications of methiozolin at 1000 g ha^{-1} , primisulfuron alone, and amicarbazone alone was $\leq 45\%$ and equivalent to the nontreated check (Table 1).

Regardless of application timing and rate, methiozolin alone did not injure Kentucky bluegrass (Table 2). Koo et al. (2013) under greenhouse conditions and McNulty and Askew (2011) under field conditions also reported Kentucky bluegrass cv. 'Midnight' safe to

methiozolin at up to 4000 g ha⁻¹. Koo et al. (2013) found methiozolin at 4000 g ha⁻¹ to injure Kentucky bluegrass 10-20%; however, the injury was transient and Kentucky bluegrass recovered completely within six wk after treatment. Rana and Askew (2016) also reported Kentucky bluegrass cv. 'Midnight II', the same cultivar used in the current study, safe to methiozolin rate of at least 2000 g ha⁻¹. Primisulfuron alone and tank mixed with methiozolin were the only treatments that had average Kentucky bluegrass injury of 4 to 6% (Table 2). Maximum Kentucky bluegrass injury from spring applications of primisulfuron alone and tank-mixed with methiozolin was not more than 25% (data not shown). However, the injury was transient and Kentucky bluegrass recovered completely within six wk after the second and final spring application of primisulfuron-containing treatments (data not shown). Lack of Kentucky bluegrass injury also agreed with Kentucky bluegrass average NDVI data, where all treatments had NDVI equal to or greater than the nontreated check (data not shown).

Hart and McCullough (2007) also reported $\leq 9\%$ Kentucky bluegrass injury following spring applications of primisulfuron with complete recovery within one mo after treatment (MAT). Amicarbazone alone and tank-mixed with methiozolin did not injure Kentucky bluegrass at any evaluation (Table 2); however, other researchers have reported amicarbazone to injure Kentucky bluegrass with increased sensitivity at higher temperatures (McCullough et al. 2010). McCullough et al. (2010) reported fall applications of amicarbazone at 100 g ha⁻¹ to injure Kentucky bluegrass 8 to 26% depending on location and greater than spring applications that caused 4 to 6% injury, 4 WAT. Kentucky bluegrass recovered completely with 6 to 8 wk after spring amicarbazone treatment (McCullough et al. 2010). In growth chamber experiments, McCullough et al. (2010) reported sequential applications of amicarbazone at 100 g ha⁻¹ to injure

Kentucky bluegrass cv. 'Midnight' approximately 0, 5 to 20, and 30 to 70% at 20 and 40 d after treatment (DAT) when grown at 10, 20, and 30 C, respectively. Average mean monthly temperatures at and during the mo of amicarbazone applications in the current study were not more than 18 C and were most likely the reason for no Kentucky bluegrass injury following spring applications of amicarbazone (Tables 2 and 3).

Roughstalk bluegrass average cover had a significant trial-by-treatment interaction ($P < 0.0001$) and was separated by trials (Table 1). At GR1, all programs that contained methiozolin in fall, excluding methiozolin mixed with amicarbazone, had less roughstalk bluegrass than the nontreated check. Methiozolin applied at 1500 g ha^{-1} four times in spring had equivalent roughstalk bluegrass cover to the better-performing fall programs and also had less cover than the nontreated check (Table 1). Roughstalk bluegrass average cover for amicarbazone, primisulfuron, or methiozolin applied only in spring at $1000 \text{ g ai ha}^{-1}$ was not different from the nontreated check (Table 1). A similar trend was observed at GR2 with the exception that, methiozolin at $1000 \text{ g ai ha}^{-1}$ split between fall and spring treatments had less roughstalk bluegrass cover than the nontreated check only when amicarbazone or primisulfuron were added to the spring treatments (Table 1). The change in efficacy between trials for the low rate of methiozolin applied in spring and fall and for the program of methiozolin mixed with amicarbazone in spring was the likely cause of the trial-by-treatment interaction for roughstalk bluegrass cover. Inconsistent efficacy of amicarbazone among trials has also been reported by other researchers (Hart and McCullough 2007).

Roughstalk bluegrass average control also had a trial-by-treatment interaction ($P < 0.0001$) and was separated by trials (Table 1). All treatments containing fall-applied methiozolin

controlled roughstalk bluegrass ≥ 67 in GR1 and GR2 studies and higher than spring-only applications of methiozolin, primisulfuron alone, and amicarbazone alone (Table 1). At GR1, methiozolin at 1500 g ha^{-1} applied four times in fall controlled roughstalk bluegrass 85%, and higher than other fall-applied methiozolin treatments, regardless of rates and tank-mixtures (Table 1). However, at GR2, the same methiozolin treatment controlled roughstalk bluegrass 89%, and equivalent to three out of the remaining five fall-applied methiozolin treatments (Table 1). Although no peer-reviewed paper has reported long-term efficacy of methiozolin for controlling annual bluegrass and roughstalk bluegrass in a fairway-height turf, several researchers have reported sequential application of methiozolin at 500 to 1000 g ha^{-1} to control annual bluegrass $\geq 85\%$, with higher control following fall, rather than spring, applications (Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013). Preliminary research by McNulty and Askew (2011) reported spring applications of methiozolin at 2000 g ha^{-1} or bispyribac-sodium at 74 g ha^{-1} applied twice at a monthly interval to control roughstalk bluegrass 60 and 90%, respectively, 4 wk after the second treatment. In the same study, roughstalk bluegrass control was not evident from any treatment 1 YALT (Askew, unpublished data). Methiozolin at 1000 g ha^{-1} applied three times in fall and spring for three yr selectively controlled roughstalk bluegrass to commercially-acceptable levels in Kentucky bluegrass fairways at Pine Ridge Country Club in South Korea (SJ Koo, personal communication). Results of the current study agree with these preliminary reports that methiozolin could have utility for roughstalk bluegrass control in Kentucky bluegrass fairways.

Annual bluegrass average cover had a significant treatment interaction ($P < 0.0001$) but no trial-by-treatment interaction ($P = 0.9602$); therefore, cover data were pooled over trials

(Table 1). Average annual bluegrass cover over the 2.5-yr period was not more than 8% following treatments with fall applications of methiozolin and less than treatments with spring-only applications or the nontreated check (Table 1). Amicarbazone and methiozolin applied only in spring had 18 to 27% average annual bluegrass cover which was less than the nontreated check (Table 1). McCullough et al. 2010 reported amicarbazone at 100 g ha⁻¹ applied twice at a three-wk interval in spring to control annual bluegrass 23 to 66% depending on location, 6 WAIT. The 2.5-yr average visually-estimated annual bluegrass control in the current study exhibited the same treatment rank as the average annual bluegrass cover data and amicarbazone controlled annual bluegrass 30% (data not shown) and within the range reported by McCullough et al (2010). Regardless of trials, fall applications of amicarbazone controlled annual bluegrass greater than spring applications; however, greater annual bluegrass control following fall applications came at the expense of increased Kentucky bluegrass injury (McCullough et al. 2010). Annual bluegrass average cover following spring applications of primisulfuron was 33% and not different than the nontreated check (Table 1). Hart and McCullough (2007) reported two late-spring applications of primisulfuron at 22 to 44 g ha⁻¹ applied one mo apart to maintain annual bluegrass cover 12 and 7%, respectively, 10 WAIT, and lower than the nontreated check. The higher annual bluegrass cover reduction in Hart and McCullough's (2007) study compared to the current study was presumably because of differences in application timing and temperatures, and also because the current study represents cover data averaged over several evaluations spanning the entire duration of the study compared with a single evaluation date. McCullough et al. (2010) did not present annual bluegrass cover data but reported two

applications primisulfuron at 0.5 kg ha^{-1} , a rate almost double of what used in the current study, applied three-wk apart to control annual bluegrass 63%.

The visual plant cover assessment ratings for Kentucky bluegrass, roughstalk bluegrass, and annual bluegrass were highly correlated with the quantitative plant cover assessed via the line-intersect method, for each of three spring assessments. Regardless of plant species, the Pearson Correlation Coefficient between visual and quantitative cover assessments was ≥ 0.91 (Table 4). Hoyle et al. (2013) evaluated multiple rating methods utilized in turfgrass weed science and reported that visual assessment is not different than quantitative assessments such as line-intersect and digital image analysis. Line-intersect analyses have been compared to visual assessments by several researchers in turfgrass sciences (Elmore et al. 2013; Gannon et al. 2015) and found to be equivalent.

At 1 YALT, Kentucky bluegrass, roughstalk bluegrass, and annual bluegrass cover (evaluated using line-intersect method) all had a significant treatment effect ($P < 0.05$) and no trial-by-treatment interaction ($P > 0.05$); therefore, cover data for all three of these species were pooled over trials (Table 1). All treatments, except amicarbazone alone, yielded Kentucky bluegrass cover higher than the nontreated check, 1 YALT (Table 1). At 1 YALT, methiozolin at 1500 g ha^{-1} applied twice in fall fb twice in spring for two consecutive yr maintained Kentucky bluegrass cover 77% and equivalent to all the treatments containing fall applications of methiozolin (67 to 75%), except methiozolin at 1000 g ha^{-1} applied only in fall (43%). Spring applications of methiozolin, primisulfuron, and amicarbazone alone maintained Kentucky bluegrass cover $\leq 52\%$, 1 YALT (Table 1). In addition, all fall-applied methiozolin treatments

maintained roughstalk bluegrass and annual bluegrass cover 2 to 8 and 5 to 13%, respectively, which were equivalent to each other within a plant species and lower than the nontreated check.

At 1 YALT, spring-applied methiozolin maintained roughstalk bluegrass and annual bluegrass cover equivalent to better-performing treatments only at higher rates of 1500 g ha⁻¹ (Table 1). Trends of increase in Kentucky bluegrass cover and decrease in roughstalk bluegrass and annual bluegrass cover at 1 YALT are similar to the 2.5-yr average plant cover (Table 1) indicating long-term efficacy of fall-applied methiozolin for selectively controlling weedy *Poa* species in Kentucky bluegrass (Tables 1 and 2). No peer-reviewed paper has reported long-term Kentucky bluegrass, annual bluegrass, and roughstalk bluegrass, maintained at fairway-height, response to methiozolin. Askew and McNulty (2014) conducted research on creeping bentgrass putting greens and reported fall and spring applications methiozolin at 500 and 750 g ha⁻¹ to reduce annual bluegrass cover 42 and 75%, respectively, at 2 yr after initial treatment.

At GR1, fall-only methiozolin treatments controlled corn speedwell (*Veronica arvensis* L.) and Persian speedwell (*Veronica persica* Poir.) 75 to 88% when evaluated in spring (data not shown). At GR2, fall-only methiozolin applications controlled corn speedwell and Persian speedwell < 35%. Fall-only methiozolin applications controlled common chickweed (*Stellaria media* (L.) Vill.) and mouseear chickweed (*Cerastium fontanum* ssp. *vulgare* (Hartman) Greuter & Burdet) 100% regardless of trial, when evaluated in the spring (data not shown). Irrespective of trial, spring-only applications of methiozolin served as effective PRE control treatments for smooth crabgrass (*Digitaria ischaemum* L.) with ≥ 95% control till 8 wk after initial spring application (data not shown). Winter-annual weed control data in current study agrees with previous research conducted at Virginia Tech (Rana and Askew 2016).

Turf and roughstalk bluegrass average NDVI had significant treatment effect ($P < 0.05$) but no trial-by-treatment interaction ($P > 0.05$); therefore, NDVI data were pooled over trials (Table 2). All the treatments with fall applications of methiozolin produced turf NDVI ≥ 0.6880 and higher than the nontreated check (Table 2). However, spring applications of methiozolin, amicarbazone alone, and primisulfuron alone had no significant advantage over the nontreated check for turf NDVI (Table 2). All methiozolin-containing treatments produced roughstalk bluegrass average NDVI 0.5700 to 0.619 and lower than non-methiozolin treatments (Table 2). Fall-only methiozolin treatments produced roughstalk bluegrass NDVI 0.5700 to 0.5760 and equivalent to methiozolin-only treatments applied twice in fall fb twice in spring but higher than other methiozolin treatments. For the most part, trends in turf and roughstalk bluegrass NDVI were in agreement with overall cover and/or control of weedy *Poa* species (Tables 1 and 2).

Turf average and 1 YALT quality had a significant treatment effect ($P = 0.0297$) but no trial-by-treatment interaction ($P = 0.9346$); therefore, quality data were pooled over trials (Table 2). Only methiozolin at 1500 g ha^{-1} applied twice in fall fb twice in spring produced average turf quality of 5.5 and higher than the nontreated check and few other treatments that had relatively lower efficacy in controlling weedy *Poa* species (Tables 1 and 2). At 1 YALT, all methiozolin-containing treatments produced turf quality ≥ 4.9 and higher than the nontreated check. Neither average nor 1 YALT turf quality was greater than or equal to minimally-acceptable turf quality of 6.0. Overall poor turf quality and lack of significant treatments differences was either because of effective control of weedy *Poa* species leaving voids in turf canopy or because of poor weed control leading to a plot with a mottled appearance of dark-green Kentucky bluegrass infested with light-green annual bluegrass and roughstalk bluegrass. Moreover, the majority of plant

response evaluations were collected during late fall/early winter or early spring, the timings at which turf was either undergoing or recovering from winter dormancy or injury and control from herbicidal treatments was at its peak.

Creeping Bentgrass Trials. When averaged over all plots at each trial, creeping bentgrass initial cover was 93 and 50% and roughstalk bluegrass initial cover was 7 and 50% at HCPR and PDRC, respectively (data not shown). Creeping bentgrass average cover had a significant trial-by-treatment interaction ($P = 0.0360$); therefore, data were separated by trials (Table 5). At HCPR, none of the treatments had an average creeping bentgrass cover different from the nontreated check, but all fall-applied methiozolin treatments, except methiozolin at 1000 g ha^{-1} split between fall and spring or tank-mixed with primisulfuron, yielded an average creeping bentgrass cover of 89 to 90% and higher than amicarbazone and bispyribac-sodium alone (Table 5). At PDRC, all methiozolin-containing treatments produced creeping bentgrass cover of 64 to 78% and higher than the nontreated check (Table 5). Regardless of trial, none of the spring-only methiozolin treatments produced creeping bentgrass cover greater than non-methiozolin treatments (Table 5).

The visual plant cover assessment ratings for creeping bentgrass and roughstalk bluegrass were highly correlated with the quantitative plant cover assessed via the line-intersect method, for each of three spring assessments. Regardless of plant species, the Pearson Correlation Coefficient between visual and quantitative cover assessments was ≥ 0.93 and agreed with the trends observed in Kentucky bluegrass trials previously described (Table 4) and other peer-reviewed research (Elmore et al. 2013; Gannon et al. 2015; Hoyle et al. 2013).

At 1 YALT, creeping bentgrass cover (evaluated using line-intersect method) had a significant trial-by-treatment interaction ($P = 0.0043$); therefore, data were separated by trials (Table 5). All methiozolin-containing treatments maintained creeping bentgrass cover $\geq 81\%$ at HCPR and $\geq 77\%$ at PDRC and higher than their respective nontreated checks (Table 5). The inherent higher creeping bentgrass cover and little to no injury from majority of the treatments (Table 6) was presumably the reason for the lack of treatment differences at HCPR and for significant trial-by-treatment interaction for creeping bentgrass average and 1 YALT cover among two trial locations (Tables 5 and 6).

Creeping bentgrass injury had a significant trial-by-treatment interaction ($P < 0.0001$); therefore, injury data were separated by trials (Table 6). Although only primisulfuron- and bispyribac-sodium-containing treatments injured creeping bentgrass at both trials, the possible source of trial-by-treatment interaction is higher injury following bispyribac-sodium applications at PDRC (Table 6). Average creeping bentgrass injury following bispyribac-sodium applications was 20% at PDRC compared to 12% at HCPR. The peak creeping bentgrass injury following fall applications of bispyribac-sodium was 78% at PDRC compared to 46% at HCPR (data not shown). The higher injury at PDRC compared to HCPR was possibly an artifact of lower monthly temperatures at PDRC compared to HCPR (Table 3). In growth chamber experiments, McCullough and Hart (2006) reported bispyribac-sodium to injure creeping bentgrass cv. 'L-93,' the same variety used in the current study, more at colder temperatures of 10 C compared with warmer temperatures of 20 and 30 C. However, bispyribac-sodium applications under lower temperatures of around 10 C did not effectively control annual bluegrass (McCullough and Hart 2006).

Bispyribac-sodium injured creeping bentgrass following both fall and spring applications. However, fall applications injured creeping bentgrass with higher and more persistent injury compared with spring applications (data not shown). Spring applications of bispyribac-sodium injured creeping bentgrass $\leq 15\%$ at 2 wk after second spring application but the injury was transient and creeping bentgrass recovered completely within 6 wk after the second spring treatment (data not shown). The higher and persistent creeping bentgrass injury following fall applications of bispyribac-sodium could be attributed to lower late-fall and winter temperatures during and after applications compared with higher temperatures in spring (Table 3). Higher creeping bentgrass sensitivity to bispyribac-sodium with decrease in temperature have also been reported under both growth chamber (McCullough and Hart 2006) and field conditions (Lycan and Hart 2006).

Regardless of trial, the highest creeping bentgrass injury from primisulfuron alone and tank-mixed with methiozolin applied in spring was 32% at 2 wk after initial spring treatment and 40% at 2 wk after second spring treatment; however, the injury was transient and creeping bentgrass recovered completely within 4 wk after second treatment (data not shown). Although there are no peer-reviewed reports of primisulfuron injury to creeping bentgrass, primisulfuron injury to Kentucky bluegrass was observed in this study and reported by several others (Affeldt 2008; Hart and McCullough 2007). Although amicarbazone did not injure creeping bentgrass in the current study, under warmer temperatures and other factors as discussed above in the Kentucky bluegrass section, amicarbazone can cause significant injury to creeping bentgrass as well (McCullough et al. 2010). McCullough et al. (2010) reported creeping bentgrass cv. 'L-93' injury of 4 to 19% at 4 wk and 6 to 44% at 6 to 8 wk after sequential fall applications of

amicarbazone at 100 g ha⁻¹. However, the same rate of amicarbazone applied in spring injured creeping bentgrass $\leq$ 5% at 2 WAT with complete recovery by 6 to 8 wk after treatment (McCullough et al. 2010).

Roughstalk bluegrass average cover had a significant trial-by-treatment interaction ($P < 0.0001$); therefore, cover data were separated by trials (Table 5). All treatments, except amicarbazone alone at PDRC had roughstalk bluegrass cover lower than the nontreated check (Table 5). Regardless of trials, treatments containing fall applications of methiozolin, except methiozolin at 1000 g ha⁻¹ applied twice in fall fb twice in spring, yielded roughstalk bluegrass cover lower than spring-only applications (Table 5). Efficacy of fall-applied methiozolin treatments for roughstalk bluegrass cover reduction or control was in agreement with trends observed in Kentucky bluegrass trials in the current study as discussed above (Tables 1 and 5). Compared with the non-treated check, bispyribac-sodium reduced roughstalk bluegrass cover 63% at PDRC against 42% at HCPR (Table 5). However, better roughstalk bluegrass cover reduction with bispyribac-sodium at PDRC came at the expense of higher and unacceptable creeping bentgrass injury, especially from fall applications that injured $\geq$ 60% and four times that of spring applications (data not shown). Bispyribac-sodium efficacy for selectively controlling roughstalk bluegrass in creeping bentgrass has been reported by other researchers but inconsistent trends depending on creeping bentgrass cultivars, trials, and temperature conditions were observed (McCullough and Hart 2006; McCullough and Hart 2011; Morton et al. 2007).

At 1 YALT, roughstalk bluegrass cover had a significant treatment effect ($P = 0.0009$) but no trial-by-treatment interaction ($P = 0.1446$); therefore, cover data were pooled over trials (Table 5). Methiozolin at 1500 g ha⁻¹ applied only in fall yielded roughstalk bluegrass cover of

5% and equivalent to all treatments containing fall applications of methiozolin (9 to 11%), except methiozolin at 1000 g ha⁻¹ applied twice in fall fb twice in spring (Table 5). Methiozolin applied in spring yielded roughstalk bluegrass cover equivalent to methiozolin at 1500 g ha⁻¹ only when the higher rate was used (Table 5). No other peer-reviewed research has evaluated roughstalk bluegrass response to methiozolin over a period of 2.5 yr and at 1 YALT. At 1 YALT, spring-only applications of methiozolin at 1000 g ha⁻¹ and bispyribac-sodium maintained roughstalk bluegrass cover 16% and equivalent to all the fall-applied methiozolin treatments but lower than methiozolin at 1500 g ha⁻¹. Over a three-yr long study, McCullough and Hart (2011) observed bispyribac-sodium to significantly suppress roughstalk bluegrass cover with essentially complete foliage elimination during summer months; however, roughstalk bluegrass regrew during fall months preventing the long-term control.

Creeping bentgrass 2.5-yr average NDVI had a significant treatment effect ($P = 0.0052$) but no trial-by-treatment interaction ($P = 0.7735$); whereas, and roughstalk bluegrass average NDVI had a significant trial-by-treatment interaction ($P = 0.0002$). Therefore, creeping bentgrass NDVI was pooled over trials but roughstalk bluegrass NDVI was separated by trials (Table 6). Bispyribac-sodium and primisulfuron tank-mixed with methiozolin produced creeping bentgrass NDVI 0.6807 and 0.6833, respectively, and lower than the nontreated check. The lower creeping bentgrass NDVI from bispyribac-sodium and primisulfuron tank-mixed with methiozolin were in agreement with creeping bentgrass average injury (Table 6). All treatments, except amicarbazone alone at HCPR, produced roughstalk bluegrass NDVI 0.5646 to 0.6689 and lower than the nontreated check (Table 5). In addition, the majority of the fall-applied

methiozolin treatments that reduced roughstalk bluegrass average cover the most resulted in lower NDVI compared to spring-only applications of methiozolin (Tables 5 and 6).

Average and 1 YALT turf quality had a significant location-by-treatment interaction ($P < 0.0001$); therefore, data were separated by locations (Table 6). Regardless of location, the nontreated check resulted in among the highest turf quality plots, contrary to what was observed at Kentucky bluegrass trials (Table 2). The better quality of untreated plots was primarily because of better management practices the golf courses aimed at managing creeping bentgrass and weedy *Poa* species to look similar to each other in terms of uniformity in color, but that becomes almost impossible with darker-green Kentucky bluegrass. The majority of treatments at HCPR produced turf quality higher than minimally-acceptable levels of 6.0; however, none of the treatments produced turf quality higher than 5.9 at PDRC. These differences are possibly because of differences in the intensity of management practices at a resort-level golf course at HCPR compared with PDRC that had a comparatively much lower budget to manage creeping bentgrass fairways. Moreover, the majority of plant response evaluations were collected during late fall/early winter or early spring, the timings at which turf was either undergoing or recovering from winter dormancy or injury and control from herbicidal treatments was at its peak. At 1 YALT, however, the improved turf quality following effective roughstalk bluegrass control was quite apparent (Tables 5 and 6). And, regardless of trials, all treatments had a turf quality of ≥ 6.6 and higher than the minimally-acceptable levels of 6.0. At HCPR, all treatments, except amicarbazone alone and bispyribac-sodium, yielded turf quality ≥ 7.7 and equivalent to the non-treated check. Although the intensity of management practices at HCPR hindered the

ability to better separate treatments for turf quality, seven out of 11 herbicidal treatments at PDRC yielded turf quality ≥ 7.6 and higher than the non-treated check.

Results from this study suggest that fall applications of methiozolin generally control roughstalk bluegrass better than spring-only applications. Methiozolin-alone at our treatment levels did not injure creeping bentgrass and Kentucky bluegrass regardless of application rate and timing. For effective and consistent long-term roughstalk bluegrass control with safety to fairway-height creeping bentgrass and Kentucky bluegrass, methiozolin at 1500 g ha^{-1} applied four times in fall or twice in fall fb twice in spring at 2-wk intervals for two consecutive yr is the best option. When using lower rates of 1000 g ha^{-1} , methiozolin should be either applied all in fall or applied twice in fall fb twice in spring with amicarbazone (primisulfuron is not yet registered for use in turf) for two consecutive yr. However, extreme care should be taken to avoid creeping bentgrass and Kentucky bluegrass varieties and temperature conditions during and after applications that could result in unacceptable amicarbazone injury to the desirable turfgrass species. Bispyribac-sodium applied twice in fall fb twice in spring for two consecutive yr was inconsistent for selectively controlling roughstalk bluegrass in creeping bentgrass.

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Table 1. Average green cover following 20 and 18 evaluations of Kentucky bluegrass, roughstalk bluegrass, and annual bluegrass over 2.5- and 1.5-yr periods for the Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2013 (GR1) and fall 2014 (GR2), respectively, and at 1 yr after last treatment (YALT) (only for GR1), where fall and/or spring herbicide programs were applied for two consecutive yr.

Herbicide program ^b				Average								
				Cover ^c				Control ^d		Cover 1 YALT ^c		
				POATR		POATR						
Fall	Apps yr ⁻¹	Spring	Apps yr ⁻¹	POAPR	GR1	GR2	POAAN	GR1	GR2	POAPR	POATR	POAAN
%												
NTC	-	-	-	25	14	20	42	-	-	13	21	55
M low	4	M low	0	66	7	3	7	75	85	43	5	13
M high	4	M high	0	69	6	5	5	85	89	67	2	8
M low	0	M low	4	37	17	30	18	42	39	38	13	30
M high	0	M high	4	45	8	15	23	52	48	52	5	20
M low	2	M low	2	63	8	11	5	67	75	67	8	7

M high	2	M high	2	75	6	4	4	75	88	77	3	5
M low	2	M low + P	2 + 2	67	3	6	7	71	84	75	3	10
M low	2	M low + A	2 + 2	60	9	7	8	68	78	72	5	6
P	0	P	2	38	11	18	33	48	26	38	13	30
A	0	A	2	32	10	34	27	38	14	27	13	43
LSD _{0.05}				14	6	11	10	4	4	19	6	17

^a Abbreviations: A, amicarbazone at 98 g ai ha⁻¹; Apps yr⁻¹, number of applications per yr; GR1, trial that initiated on October 21, 2013; GR2, trial that initiated on October 22, 2014; LSD, Fishers Protected Least Significant Difference at 5% level of significance; M low, methiozolin at 1000 g ha⁻¹; M high, methiozolin at 1500 g ha⁻¹; POAAN, *Poa annua* L. (annual bluegrass); POAPR, *Poa pratensis* L. (Kentucky bluegrass); POATR, *Poa trivialis* L. (roughstalk bluegrass); P, primisulfuron at 26.3 g ha⁻¹; NTC; nontreated check; YALT, yr after last treatment.

^b For both GR1 and GR2, herbicide programs were applied in two consecutive yr for a total of 8 applications for methiozolin-containing treatments and 4 applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

^c Plant cover was visually estimated by species as percent green tissue on a 0 to 100% scale and averaged over 20 and 18 evaluations made during a 2.5-yr period for GR1 and 1.5-yr for GR2, respectively. Cover at 1 YALT was based on line-intersect counts where species present

at each of 358 intersects were assessed in each 5-m² plot on May 15, 2016. Kentucky bluegrass and annual bluegrass average and 1 YALT cover had no yr-by-treatment interaction ($P > 0.05$); therefore, cover data were pooled over two yr. Roughstalk bluegrass had a significant yr-by-treatment interaction only for average cover ($P = 0.0030$) but not for cover at 1 YALT ($P > 0.05$); therefore, data for roughstalk bluegrass average cover were separated by yr and cover at 1 YALT were pooled over yr.

^d Roughstalk bluegrass control was visually estimated as percent reduction in green tissue on a 0 to 100% scale, where 0 indicates no reduction in green tissue and 100 indicates no green cover and averaged over 20 and 18 evaluations made during a 2.5-yr period for GR1 and 1.5-yr for GR2, respectively. Roughstalk bluegrass average control had a significant yr-by-treatment interaction ($P < 0.0001$); therefore, control data were separated by yr.

Table 2. Average Kentucky bluegrass injury, roughstalk bluegrass NDVI, and turf NDVI and quality following 20 and 18 evaluations over 2.5- and 1.5-yr periods for the Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2013 (GR1) and fall 2014 (GR2), respectively, and at 1 yr after last treatment (YALT) (only for GR1), where fall and/or spring herbicide programs were applied for two consecutive yr.

Herbicide program ^b				Injury ^c	NDVI ^d		Turf quality ^e	
Fall	Apps yr ⁻¹	Spring	Apps yr ⁻¹	POAPR	POATR	Turf	2.5-yr Avg.	1 YALT
				— % —	— 0-1 —		— 1-9 —	
NTC	-	-	-	-	0.7079	0.6716	4.8	4.2
M low	4	M low	0	0	0.5700	0.7009	5.0	5.1
M high	4	M high	0	0	0.5760	0.6880	5.1	5.4
M low	0	M low	4	0	0.6191	0.6663	4.8	4.9
M high	0	M high	4	0	0.6043	0.6735	5.1	5.2
M low	2	M low	2	0	0.5991	0.7146	5.0	5.5
M high	2	M high	2	0	0.5976	0.7182	5.5	5.8
M low	2	M low + P	2 + 2	6	0.6141	0.7152	5.2	5.7

M low	2	M low + A	2 + 2	0	0.6074	0.6928	5.0	5.7
P	0	P	2	4	0.6695	0.6797	5.0	5.0
A	0	A	2	0	0.6655	0.6563	4.9	4.5
LSD _{0.05}				1	0.0323	0.0294	0.4	0.5

^a Abbreviations: A, amicarbazone at 98 g ai ha⁻¹; Apps yr⁻¹, number of applications per yr; LSD, Fishers Protected Least Significant Difference at 5% level of significance; M low, methiozolin at 1000 g ha⁻¹; M high, methiozolin at 1500 g ha⁻¹; POAAN, *Poa annua* L. (annual bluegrass); POAPR, *Poa pratensis* L. (Kentucky bluegrass); POATR, *Poa trivialis* L. (roughstalk bluegrass); P, primisulfuron at 26.3 g ha⁻¹; NTC; nontreated check; YALT, yr after last treatment.

^b Herbicide programs were applied in two consecutive yr for a total of 8 applications for methiozolin-containing treatments and 4 applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals

^c Kentucky bluegrass injury was visually estimated as percent reduction in green tissue on a 0 to 100% scale, where 0 indicates no reduction in green tissue and 100 indicates no green tissue, and averaged over 20 and 18 evaluations made during a 2.5-yr period for GR1 and 1.5-yr for GR2, respectively. Kentucky bluegrass average injury had a significant yr-by-treatment interaction ($P = 0.0135$); however, Kentucky bluegrass injury also had a significant treatment effect ($P = 0.0012$) with F-values greater than four times compared to yr-by-treatment interaction; therefore, Kentucky bluegrass average injury data were pooled over two yr.

^d Overall turf NDVI data were collected using multispectral analyzer (Crop Circle™ Model ACS-210); whereas, roughstalk bluegrass NDVI data were collected using spectroradiometer (Spectral Evolution PSR-1100). The NDVI measurements for both turf and roughstalk bluegrass were averaged over 20 and 18 evaluations made during a 2.5-yr period for GR1 and 1.5-yr for GR2, respectively. Turf and roughstalk bluegrass average NDVI had no significant yr-by-treatment interaction ($P > 0.05$); therefore, NDVI data were pooled over two yr.

^e Turf quality was assessed based on a 1 to 9 scale, where 9 is ideal turf quality, 6 is minimally acceptable turf quality, and 1 is a complete loss of green turf. Average quality represents turf quality measurements averaged over 20 and 18 evaluations made during a 2.5-yr period for GR1 and 1.5-yr for GR2, respectively. Neither average nor 1 YALT turf quality measurements had a significant yr-by-treatment interaction ($P > 0.05$); therefore, turf quality data were pooled over two yr.

Table 3. Mean monthly temperatures, during mo of herbicide application program at Kentucky bluegrass trials - GR1 and GR2 in Blacksburg, VA, and creeping bentgrass trials – HCPR and PDRC in Meadows of Dan and Radford, respectively.

Mo	Monthly mean temperature ^b											
	GR1			GR2			HCPR			PDRC		
	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min
°C												
Yr 1												
Oct	20	12	1	19	12	6	22	16	4	20	13	1
Nov	15	4	-6	14	4	-6	18	7	-2	16	5	-6
Dec	14	3	-4	9	3	-2	19	6	-3	14	3	-4
Apr	18	12	3	18	12	6	19	14	6	18	12	3
May	23	17	9	22	18	10	24	20	11	22	17	9
Jun	24	21	17	25	22	15	26	24	19	25	22	17
Yr 2												
Oct	19	12	6	18	12	5	22	16	8	21	13	6
Nov	14	4	-6	19	9	1	16	7	-2	15	4	-6

Dec	9	3	-2	17	8	0	12	7	1	13	4	-2
Apr	18	12	6	21	12	-1	21	15	8	18	13	7
May	22	18	10	22	16	7	24	21	12	22	19	10
Jun	25	22	15	25	21	16	28	24	18	26	23	16

^a Abbreviations: Apr, April; Avg, average; Dec, December; GR1, Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2013; GR2, Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2014; HCPR, creeping bentgrass site at Primland Resort in Meadows of Dan, VA; Jun, June; Nov, November; Oct, October; PDRC, creeping bentgrass site at Pete Dye River Course of Virginia Tech in Radford, VA.

^b Temperature data for a given location were accessed from online weather information website - wunderground.com.

Table 4. Correlation between visually estimated and line-intersect method assessed plant cover at 1 yr after last treatment (YALT).

Cover 1 YALT ^b	Pearson correlation coefficient (P-value) ^c
	———— -1 to +1 ————
POAPR (avg GR1 and GR2)	0.9099 (<0.0001)
POATR (avg GR1 and GR2)	0.9633 (<0.0001)
POAAN (avg GR1 and GR2)	0.9323 (<0.0001)
AGSST HCPR	0.9299 (<0.0001)
POATR HCPR	0.9738 (<0.0001)
AGSST PDRC	0.9514 (<0.0001)
POATR PDRC	0.9714 (<0.0001)

^a Abbreviations: AGSST, *Agrostis stolonifera* L. (creeping bentgrass); Avg., average; GR 1, Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2013; GR2, Kentucky bluegrass site in Blacksburg, VA at which treatments were initiated in fall 2014; HCPR, creeping bentgrass site at Primland Resort in Meadows of Dan, VA; PDRC, creeping bentgrass site at Pete Dye River Course of Virginia Tech in Radford, VA; POAAN, *Poa annua* L. (annual bluegrass); POAPR, *Poa pratensis* L. (Kentucky bluegrass); POATR, *Poa trivialis* L. (roughstalk bluegrass); YALT, yr after last treatment.

^b Plant cover was visually estimated by species as percent green tissue on a 0 to 100% scale and also based on line-intersect counts where species present at each of 239, 358, and 794 intersects were assessed in each 3.34-, 5.01-, and 11.1-m² plots at HCPR, GR, and PDRC, respectively, on April 29, 2016. Cover of each species at GR was pooled over two studies (yr. 1 and yr. 2)

because of no significant yr interaction ($P > 0.05$). However, at HCPR and PDRC sites, plant cover had a significant location interaction ($P < 0.05$). Therefore, cover data were separated by locations.

^c Pearson correlation coefficients along with their respective P-values were calculated by subjecting plant cover assessed via two methods (visually assessment and line-intersect method) to PROC CORR in SAS.

Table 5. Average green cover following 20 evaluations of creeping bentgrass and annual bluegrass over a 2.5-yr period and at 1 yr after last treatment (YALT), where fall and/or spring herbicide programs were applied for two consecutive yr.

Herbicide program ^b				2.5-yr average cover ^c				Cover 1 YALT ^c		
				AGSST		POATR		AGSST		POATR
				HCPR	PDRC	HCPR	PDRC	HCPR	PDRC	
Fall	Apps yr ⁻¹	Spring	Apps yr ⁻¹	%						
NTC	-	-	-	85	51	12	43	70	62	33
M low	4	M low	0	89	72	5	10	90	91	10
M high	4	M high	0	89	67	2	7	95	96	5
M low	0	M low	4	87	67	7	27	90	78	16
M high	0	M high	4	87	68	7	26	90	86	12
M low	2	M low	2	86	64	7	20	81	77	21
M high	2	M high	2	90	78	4	8	87	95	9
M low	2	M low + P	2 + 2	87	66	3	7	94	87	10
M low	2	M low + A	2 + 2	90	77	5	12	91	88	11
P	0	P	2	86	62	7	27	85	52	26

A	0	A	2	81	61	10	34	72	55	37
B	2	B	2	81	61	7	16	72	80	16
LSD _{0.05}				7	13	2	11	10	15	8

^a Abbreviations: A, amicarbazone at 98 g ai ha⁻¹; AGSST, *Agrostis stolonifera* L. (creeping bentgrass); bispyribac-sodium at 24.7 g ha⁻¹; LSD, Fishers Protected Least Significant Difference at 5% level of significance; M low, methiozolin at 1000 g ha⁻¹; M high, methiozolin at 1500 g ha⁻¹; Apps yr⁻¹, number of applications per yr; HCPR, trial at Primland Resort in Meadows of Dan, VA; NTC; nontreated check; P, primisulfuron at 26.3 g ha⁻¹; PDRC, trial at Pete Dye River Course of Virginia Tech in Radford, VA; POATR, *Poa trivialis* L. (roughstalk bluegrass); YALT, yr after last treatment.

^b For both studies (HCPR and PDRC), herbicide programs were applied in two consecutive yr for a total of 8 applications for methiozolin-containing and bispyribac-sodium treatments, and 4 applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

^c Plant cover was visually estimated by species as percent green tissue on a 0 to 100% scale and averaged over 20 evaluations made during a 2.5-yr period. Cover at 1 YALT was based on line-intersect counts where species present at each of 794 and 239 intersects were assessed in each 3.34- and 11.1-m² plots at HCPR and PDRC, respectively, on April 29, 2016. For both creeping bentgrass and roughstalk bluegrass, 2.5-yr average and 1 YALT cover had a significant location interaction ($P < 0.05$); therefore, cover data were separated by yr.

Table 6. Average creeping bentgrass injury, creeping bentgrass and roughstalk bluegrass NDVI, and turf quality following 20 evaluations over a 2.5-yr period and turf quality at 1 yr after last treatment (YALT), where fall and/or spring herbicide programs were applied for two consecutive yr.

Herbicide program ^b				Avg. injury ^c		Average NDVI ^d			Turf quality ^e			
				AGSST		POATR			2.5-yr avg.		1 YALT	
Fall	Apps yr ⁻¹	Spring	Apps yr ⁻¹	HCPR	PDRC	AGSST	HCPR	PDRC	HCPR	PDRC	HCPR	PDRC
				——%——		———0-1———			———1-9———			
NTC	-	-	-	0	0	0.7036	0.7093	0.7091	6.5	5.7	7.9	6.8
M low	4	M low	0	0	0	0.7038	0.6285	0.6078	6.3	5.5	8.0	7.8
M high	4	M high	0	0	0	0.7069	0.6213	0.6113	6.2	5.1	8.2	8.1
M low	0	M low	4	0	0	0.7079	0.6689	0.7098	6.3	5.8	7.9	7.2
M high	0	M high	4	0	0	0.6942	0.6452	0.6824	6.3	5.9	7.8	7.6
M low	2	M low	2	0	0	0.6960	0.6266	0.6511	6.1	5.3	7.6	7.2
M high	2	M high	2	0	0	0.6987	0.6285	0.6120	6.3	5.4	7.7	8.1
M low	2	M low + P	2 + 2	4	4	0.6833	0.6021	0.5646	5.9	4.2	8.1	7.7
M low	2	M low + A	2 + 2	0	0	0.6993	0.6259	0.6486	6.5	5.5	7.8	7.9

P	0	P	2	8	6	0.6929	0.6345	0.6904	6.3	5.8	7.9	6.6
A	0	A	2	0	0	0.7168	0.6793	0.6628	6.5	5.7	7.4	6.6
B	2	B	2	12	20	0.6807	0.6449	0.6013	6.2	5.0	7.2	7.7
LSD _{0.05}				1	2	0.0157	0.0301	0.0350	0.2	0.5	0.5	0.6

^a Abbreviations: A, amicarbazone at 98 g ai ha⁻¹; AGSST, *Agrostis stolonifera* L. (creeping bentgrass); bispyribac-sodium at 24.7 g ha⁻¹; LSD, Fishers Protected Least Significant Difference at 5% level of significance; M low, methiozolin at 1000 g ha⁻¹; M high, methiozolin at 1500 g ha⁻¹; Apps yr⁻¹, number of applications per yr; HCPR, trial at Primland Resort in Meadows of Dan, VA; NTC; nontreated check; P, primisulfuron at 26.3 g ha⁻¹; PDRC, trial at Pete Dye River Course of Virginia Tech in Radford, VA; POATR, *Poa trivialis* L. (roughstalk bluegrass); YALT, yr after last treatment.

^b For both studies (HCPR and PDRC), herbicide programs were applied in two consecutive yr for a total of 8 applications for methiozolin-containing and bispyribac-sodium treatments, and 4 applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

^c Creeping bentgrass injury was visually estimated as percent reduction in green tissue on a 0 to 100% scale, where 0 indicates no reduction in green tissue and 100 indicates no green tissue and averaged over 20 evaluations made during a 2.5-yr period. Creeping bentgrass average injury had a significant location-by-treatment effect ($P < 0.0001$); therefore, injury data were separated by locations.

^d Creeping bentgrass and roughstalk bluegrass NDVI data were collected using spectroradiometer (Spectral Evolution PSR-1100) averaged over 20 evaluations made during a 2.5-yr period. Creeping bentgrass and roughstalk bluegrass average NDVI had a significant location interaction ($P < 0.05$); therefore, NDVI data were separated by locations.

^e Turf quality was assessed based on a 1 to 9 scale, where 9 is ideal turf quality, 6 is minimally acceptable turf quality, and 1 is a complete loss of green turf. The 2.5-yr average quality represents turf quality measurements averaged over 20 evaluations made during a 2.5-yr period and the final evaluation made on April 29, 2016, respectively. Both average and 1 YALT turf quality measurements had a significant location interaction ($P < 0.05$); therefore, turf quality data were separated by locations.

Chapter 4. Response of 110 Kentucky Bluegrass Varieties and Winter Annual Weeds to Methiozolin

Sandeep S. Rana and Shawn D. Askew *

Methiozolin is a new isoxazoline herbicide that has scarcely been tested in Kentucky bluegrass turf. A field trial was conducted in Blacksburg, VA to determine the response of 110 Kentucky bluegrass varieties and winter annual weeds to sequential fall applications of methiozolin. At 1.5 and 6 months after initial treatment (MAIT), Kentucky bluegrass injury I_{30} values (predicted methiozolin rate that causes 30% Kentucky bluegrass injury) ranged between 3.4 to more than 10 times the recommended methiozolin rate for annual bluegrass control. Methiozolin at all rates reduced cover of annual bluegrass, common chickweed, corn speedwell, hairy bittercress, mouseear chickweed, and Persian speedwell, but increased cover of parsley-piert. For all varieties, methiozolin at 2 kg ha^{-1} increased Kentucky bluegrass cover, turf quality, and turf normalized difference vegetative index (NDVI) relative to the nontreated check at 6 MAIT. Kentucky bluegrass relative cover change (RCC) was attributed primarily to weed control but was inversely correlated with methiozolin rates because of increased weed control and reduced Kentucky bluegrass growth. Despite the decline in RCC with increasing methiozolin rates, most Kentucky bluegrass varieties treated with the highest methiozolin rate (6 kg ha^{-1}) still had greater

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Kentucky bluegrass cover than the nontreated check at 6 MAIT. Results from this study indicate that two fall applications of methiozolin at rates beyond that previously reported for annual bluegrass control can safely be applied to a broad range of Kentucky bluegrass varieties spanning most of the known genetic classifications.

Nomenclature: Methiozolin, 5-(2,6-difluorobenzyl)oxymethyl-5-methyl-3-(3-methylthiophen-2-yl)-1,2-isoxazoline, code names: EK-5229, SJK-03, and MRC-01; annual bluegrass, *Poa annua* L.; common chickweed, *Stellaria media* (L.) Vill.; corn speedwell, *Veronica arvensis* L.; hairy bittercress, *Cardamine hirsuta* L.; mouseear chickweed, *Cerastium fontanum* ssp. *vulgare* (Hartman) Greuter & Burdet; parsley-piert, *Aphanes arvensis* L.; Persian speedwell, *Veronica persica* Poir.; creeping bentgrass, *Agrostis stolonifera* L.; Kentucky bluegrass, *Poa pratensis* L.

Keywords: Annual bluegrass control, I₃₀, Kentucky bluegrass genetic classification, Kentucky bluegrass variety classification, NDVI, turfgrass injury, turfgrass quality, winter annual weeds.

One of the major challenges in maintaining Kentucky bluegrass (*Poa pratensis* L.) as a desirable turf is the presence of weedy annual bluegrass (*Poa annua* L.). Because of light-green color, unsightly seedheads, shallow root system, and poor disease, insect, heat, drought, and wear tolerance, annual bluegrass reduces the aesthetics, functionality, and quality of Kentucky bluegrass turf (Beard et al. 1978; Lush 1989; Sprague and Burton 1937). Consequently, annual bluegrass infestation in Kentucky bluegrass adds to turf management costs by increasing water and fungicide needs (Hart and McCullough 2007).

Cultural methods can help reduce annual bluegrass competitiveness (Beard et al. 1978), but effective control warrants chemical options for selective control of annual bluegrass in Kentucky bluegrass, which are limited. Late-summer application of PRE herbicides in the mid-Atlantic region can interfere with successful overseeding operations in both athletic fields and golf course fairways (Dernoeden 1998). The effectiveness of PRE herbicides is further limited by the presence of perennial biotypes of annual bluegrass or persistent survival of annual biotypes, depending on environmental conditions. Therefore, the major portion of selective annual bluegrass control in Kentucky bluegrass relies on POST herbicides.

Amicarbazone and ethofumesate are currently the only herbicides registered to control annual bluegrass POST in Kentucky bluegrass. Amicarbazone, a photosystem II-inhibiting herbicide, controls annual bluegrass in fall or spring but the use of amicarbazone in fall is discouraged because of a higher potential for injury to Kentucky bluegrass (McCullough et al. 2010). Ethofumesate can control annual bluegrass POST, but previous studies suggest consistency of control and Kentucky bluegrass tolerance can vary among locations (Adams 1989; Dernoeden and Turner 1988).

Bispyribac-sodium, methiozolin, and primisulfuron are among the more promising experimental herbicides that have been evaluated in recent years for POST annual bluegrass control in cool-season grasses. Bispyribac-sodium is a pyrimidinylthiobenzoate herbicide that is registered for annual bluegrass in some cool-season grasses (Anonymous 2010b), but annual bluegrass control has been inconsistent in several studies and Kentucky bluegrass is not among the registered turfgrass species. Fall and summer applications of bispyribac-sodium controls annual bluegrass better than applications made during colder months, and bispyribac-sodium causes severe injury to Kentucky bluegrass, regardless of application timing (Hart and McCullough 2007, Shortell et al. 2008). Primisulfuron is a sulfonylurea herbicide that has controlled annual bluegrass in Kentucky bluegrass and creeping bentgrass (*Agrostis stolonifera* L.) (Hart and McCullough 2007), but there are concerns regarding Kentucky bluegrass safety with primisulfuron (Affeldt et al. 2008; Hart and McCullough 2007; Mueller-Warrant et al. 1997). Moreover, the programs used by Hart and McCullough (2007) exceeded the maximum annual use rate for primisulfuron (40.5 g ai ha⁻¹) in crops (Anonymous 2010a). The severity of Kentucky bluegrass injury by bispyribac-sodium and limited annual use rate of primisulfuron have likely prevented these two active ingredients from commercial use in Kentucky bluegrass turf.

Methiozolin is a new isoxazoline herbicide being developed by Moghu Research Center (BVC 311, KRIBB, Yuseong, Daejeon 305-333, Korea) for use in turfgrass. Currently, much of the research with methiozolin focuses on controlling annual bluegrass on putting greens. According to work conducted by the Moghu Research Center and several other researchers in the United States, methiozolin use on golf putting greens will vary by geography, but annual

bluegrass can be controlled POST with 0.5 to 1 kg ha⁻¹ applied two to five times per year (Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013; Moghu 2016; Xiong et al. 2015). Once existing annual bluegrass is controlled, new seedling annual bluegrass populations can be prevented with methiozolin at 0.5 kg ha⁻¹ applied once in spring and fall (Askew and McNulty 2014). Researchers in the United States and South Korea have also reported methiozolin at 0.5 to 1 kg ha⁻¹ to selectively control annual bluegrass in creeping bentgrass (Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013). Although little is known about methiozolin efficacy for annual bluegrass control in fairway-height turf, previous research in Blacksburg, VA, and Daejeon, South Korea, has reported methiozolin controls annual bluegrass in higher-cut turf at rates twice (1 kg ha⁻¹) that needed on putting greens (SJ Koo, personal communication; McNulty and Askew 2011).

McNulty and Askew (2011) reported methiozolin at 1.5 to 2 kg ha⁻¹ applied twice controlled annual bluegrass 84 and 94%, respectively, with no injury to Kentucky bluegrass maintained at lawn height (3.81 cm). In a greenhouse study, methiozolin at 1 kg ha⁻¹ controlled annual bluegrass with GR₅₀ (50% growth rate inhibition) values of 23, 52, 104, and 218 g ha⁻¹ at PRE, and at the two-, four- and eight-leaf stage, respectively, and was safe to Kentucky bluegrass (Koo et al. 2014). Methiozolin at 1 kg ha⁻¹ applied three times in fall and spring controlled roughstalk bluegrass (*Poa trivialis* L.) without injuring Kentucky bluegrass during a period of 3 yr (SJ Koo, personal communication). The current knowledge about methiozolin strongly suggests that methiozolin can be used safely in some Kentucky bluegrass varieties for controlling annual and roughstalk bluegrass. However, there exists a significant amount of

genetic diversity among Kentucky bluegrass varieties, which can vary a great deal in response to a given herbicide (Shortell et al. 2006, 2008, 2009).

Kentucky bluegrass varieties have been reported to exhibit differential response to herbicides that are used for annual bluegrass control. Mueller-Warrant et al. (1997) evaluated the response of 12 Kentucky bluegrass varieties to primisulfuron and reported Kentucky bluegrass injury was affected by application date, application rate, and variety; and Kentucky bluegrass injury varied 6 to 43% among varieties. Primisulfuron at 40.5 g ha⁻¹ applied in December injured Kentucky bluegrass more than the same rate applied in November or when the rate was split in half. In another study, Affeldt et al. (2008) reported primisulfuron injured some Kentucky bluegrass varieties more than others and reported seed yield was reduced in 6 of 15 varieties. Shortell et al. (2008) reported Kentucky bluegrass injury varied between 8 to 93% among 55 varieties following sequential applications of bispyribac-sodium at 188 g ha⁻¹ followed by 281 g ha⁻¹, 8 wk after initial treatment (WAIT). This variability in response of the different Kentucky bluegrass varieties to the same herbicide was attributed, in part, to variable ploidy levels and the unique apomictic breeding behavior of Kentucky bluegrass species (Raggi et al. 2007). The apomixes in Kentucky bluegrass results in true-to-type seed because of reduced outcrossing which reduces recombination and fixes hybrid vigor (Bashaw and Funk 1987; Bicknell and Koltunow 2004; Funk 2000; Turgeon 1999). This unique breeding behavior in Kentucky bluegrass leads to many distinct phenotypes which may vary in agronomic and morphological traits, and vary in tolerance to summer stress, drought, heat, and disease tolerance (Bonos and Murphy 1999; Bonos et al. 2000, 2006; Czembor et al. 2001; Shortell et al. 2006; Wang and Huang 2004).

Methiozolin has the potential to selectively control annual and roughstalk bluegrass in Kentucky bluegrass. Although methiozolin was found safe in some Kentucky bluegrass varieties in the United States and South Korea (Koo et al. 2014; McNulty and Askew 2011), further research is needed to evaluate the impact of methiozolin over a broader spectrum of Kentucky bluegrass varieties. Therefore, research was conducted to evaluate intraspecific variability in injury, NDVI, and plant cover response among 110 Kentucky bluegrass varieties and several weeds maintained at fairway height to sequential applications of methiozolin herbicide at various rates.

MATERIALS AND METHODS

Field trials were conducted from fall 2011 through spring 2012 and from fall 2013 through spring 2014 at the Virginia Tech Turfgrass Research Center (TRC; 37.21611°N, 80.411111°W) in Blacksburg, VA. Permission was granted to use a 5-yr-old Kentucky bluegrass National Turfgrass Evaluation Program (NTEP, Baltimore, MD) trial site for this study. Soil at the NTEP site was a Groseclose (fine, mixed, semiactive, mesic Typic Hapludult) with a pH of 5.1 and 4% organic matter. The site was maintained at 1.5-cm and mowed twice weekly with a reel mower (Toro Reelmaster® 5510, Toro Company, 8111 Lyndale Avenue S, Bloomington, MN 55420) with clippings returned. Fertility, irrigation, pest control, and other inputs were added as needed to simulate golf fairway maintenance. The NTEP site had 110 Kentucky bluegrass varieties. These varieties represent a broad range of diversity among Kentucky bluegrass varieties and within the major Kentucky bluegrass varietal-classification types (Honig 2011).

The experiment was arranged in a randomized complete block split-plot design with 110 main plots, four subplots, and three replications, for 1320 experimental units. The main plots consisted of 110 Kentucky bluegrass varieties. Each 1.5 m-by-1.5 m Kentucky bluegrass variety main plot was subdivided equally into four 0.38 m-by-1.5 m subplots, which were treated twice at 4-wk intervals with methiozolin (MRC-01 250 g L⁻¹ EC, Moghu Research Center, Daejeon, South Korea) at 0, 2, 4, and 6 kg ha⁻¹, respectively. Treatments were randomly assigned to subplots within each main plot. Methiozolin rates used in the study were two-, four-, and six-times higher than that needed to control annual bluegrass in Kentucky bluegrass (Koo et al. 2014; McNulty and Askew 2011). The higher methiozolin rates used in this study mimic accidental overspray in the field and represent a conservative approach to assessing turf response that should yield maximum varietal differences. Treatments were applied with a single-nozzle CO₂-pressurized backpack sprayer equipped with TTI11004 nozzles (Tee Jet Technologies, 1801 Business Park Drive, Springfield, IL 62703), which delivered 281 L ha⁻¹ of spray solution at 290 kPa. The site lay dormant for 1 yr between trial repetition and subplots were rotated 90 degrees and re-randomized for the second trial to ensure that there were no residual methiozolin effects from the first trial. The first methiozolin application was applied on October 14, 2011 for the first trial and on November 17, 2013 for the second trial.

Data were collected at 2, 4, 6, 14, and 26 WAIT. Data assessed included Kentucky bluegrass, annual bluegrass, and broadleaf weed cover; Kentucky bluegrass injury; turf quality and turf NDVI. Kentucky bluegrass and annual bluegrass cover were assessed visually at all rating dates; whereas, data for broadleaf weed cover was assessed only at the final spring rating, 6 mo after initial treatment (MAIT). To better determine the influence of methiozolin rates on

Kentucky bluegrass cover in lieu of variability in inherent cover among varieties, Kentucky bluegrass relative cover change (RCC) was calculated for each treated subplot relative to the corresponding nontreated subplot in each variety main plot as follows:

$$RCC_t = [(C_t - C_n)/C_n] \times 100 \quad [1]$$

where RCC_t is the relative cover change of a treated subplot, C_t is the observed percentage of Kentucky bluegrass cover from a treated subplot, and C_n is the observed percentage of Kentucky bluegrass cover from the adjacent nontreated subplot in a given variety main plot.

Kentucky bluegrass RCC at 6 MAIT was subjected to linear regression against methiozolin rates to calculate 660 intersects and slopes that included all levels of year-by-variety-by-replicate interaction, using the PROC REG function in SAS software (version 9.2, SAS Institute, 100 SAS Campus Drive, Cary, NC 27515-2414).

Visual estimations of Kentucky bluegrass injury were taken at all evaluation dates after methiozolin applications on a 0 to 100% scale based on an estimation of the reduction in green tissue compared with nontreated checks, where 0% was no injury, 30% was maximum acceptable injury, and 100% was complete loss of all green tissue in plots and apparent death of plants (Frans et al. 1986). The injury to Kentucky bluegrass in fall was primarily stunting and enhanced winter-associated leaf-tip necrosis; whereas, in spring, the injury manifested as stunted growth reducing Kentucky bluegrass ability to fill in voids left by dead weeds. Because 30% injury is the threshold of commercial acceptability, Kentucky bluegrass injury I_{30} values were generated to estimate the methiozolin rate needed to injure Kentucky bluegrass 30%. The injury data for each Kentucky bluegrass main plot was first subjected to an exponential function:

$$y = \exp(ax) \quad [2]$$

where y is visually-estimated Kentucky bluegrass injury, a is an estimated parameter that controls the rate of Kentucky bluegrass injury ascent as methiozolin rate increases, and x is methiozolin rate. Estimated parameters based on the least sums of squares were generated via the Gauss-Newton iterative method in PROC NLIN in SAS software. The I_{30} values were generated by setting the value of y to 30% injury and solving for x to generate 660 I_{30} values that represented all combinations of the yr by variety, and then, analyzing statistically as described for other variables.

Turf quality was assessed at all evaluation dates and was based on a one to nine scale, where nine was ideal turf quality with uniform and dark green turf, six was minimally acceptable turf quality, and one was a complete loss of green turf. Turf NDVI was collected at all rating dates using a multispectral analyzer (Crop Circle™ model ACS-210, Holland Scientific Inc., 6001 South 58th Street, Lincoln, NE 68516).

Data for each response variable were tested for normality using PROC UNIVARIATE and Shapiro-Wilk statistic in SAS software. Homogeneity of variance was assessed using Levene's test on one-way ANOVAs for main effects or all possible combinations of Kentucky bluegrass variety by methiozolin rate separately by year using the HOVTEST WELCH option in the MEANS statement of PROC GLM in SAS software (Welch 1951). Homogeneity of variance was further assessed by visually inspecting residuals and related diagnostics using the DIAGNOSTICS option in PROC PLOT in SAS software. When needed, data were transformed to the log or arcsin square root to meet assumptions of ANOVA. In such cases where transformation was needed, data were back transformed for presentation clarity. Kentucky bluegrass cover; turf quality, turf NDVI; Kentucky bluegrass RCC intersect and slope data were

then subjected to ANOVA using PROC GLM in SAS software with the sum of squares partitioned to reflect the effects of block, year, Kentucky bluegrass variety, methiozolin rate, variety-by-rate, and all possible interactions with the year. Main effects and interactions were tested using the mean square error associated with each effect's interaction with the year, which was considered random (McIntosh 1983). In the case of I_{30} values, methiozolin rate effects were not included in the model. Because weeds were not distributed uniformly in all variety main plots, only main plots in which a given weed was present in the nontreated subplot were used in the analysis and these were considered as replications in a completely randomized design. The weed cover data were then subjected to a combined ANOVA using PROC MIXED in SAS software with the sum of squares partitioned to reflect the effects of replication, year, methiozolin rate, and year by rate. Where appropriate, turf quality, turf NDVI, and weed cover data were regressed against methiozolin rates using SigmaPlot (v.11.0, Systat Software Inc., 1735 Technology Drive, Suite 430 San Jose, CA 95110). Coefficients of determination (R^2) for nonlinear equations were calculated by subtracting the ratio of the residual sums of squares to the corrected total sum of squares from 1 as performed by other researchers (Askew and Wilcut 2001; Draper and Smith 1981; Jasieniuk et al. 1999). Means for each response variable were separated using Fisher's protected LSD at the 5% level of significance.

RESULTS AND DISCUSSION

Kentucky bluegrass injury at 1.5 MAIT had a significant year-by-variety-by-rate interaction ($P < 0.0001$; data not shown) and associated I_{30} values had a significant year-by-variety interaction ($P < 0.0001$; Table 1). This evaluation date was two weeks after the second

methiozolin treatment. When averaged over 2 yr, 3 replicates, and 110 varieties, Kentucky bluegrass treated twice with methiozolin at 2, 4, and 6 kg ha⁻¹ was injured 3, 14, and 26%, respectively with standard errors of 0.23, 0.45, and 0.68%, respectively (data not shown). The lowest I₃₀ value for Kentucky bluegrass injury at 1.5 MAIT was 3.4 kg ha⁻¹ in 2011 and 5.1 kg ha⁻¹ in 2013 (Table 1) indicating that considerably more methiozolin than the amount needed to control weedy annual bluegrass (Brosnan et al. 2013; Koo et al. 2014) would be required to injure Kentucky bluegrass at commercially-unacceptable levels. Most Kentucky bluegrass varieties had an I₃₀ value of greater than 6 kg ha⁻¹ at 1.5 MAIT (Table 1). At 1.5 MAIT, only 7 of 110 Kentucky bluegrass varieties exhibited an I₃₀ value lower than 4 kg ha⁻¹ and all of these occurred only in 2011 (Table 1). Yu and McCullough (2014) reported methiozolin rates greater than 6.72 and 4.2 kg ha⁻¹ were required to injure Kentucky bluegrass cv. ‘Midnight’ 20% at 2 and 4 weeks after treatment. At 1.5 MAIT, our research determined I₃₀ values for Kentucky bluegrass cv. ‘Midnight’ to be 5.0 and 6.5 kg ha⁻¹ in 2011 and 2013, respectively (Table 1), rates that are comparable to those causing 20% injury in the study by Yu and McCullough (2013). Kentucky bluegrass injury from methiozolin was manifested as height reduction and enhanced winter-associated leaf tip necrosis. Although leaf-tip necrosis of Kentucky bluegrass could be found in nontreated plots presumably from cold injury, their frequency appeared to be greater in treated plots and associated stunted leaf growth made the necrotic leaf tips more conspicuous. Average monthly temperatures during winter ranged from 2 to 4 C in 2011 to -3 to 3 C in 2013 (Table 2). Both the intensity and duration of cold weather was greater in 2013 compared with 2011 (Table 2) and likely contributed to the significant year interaction for I₃₀ (Table 1). These data suggest that two monthly applications of methiozolin at rates below 3.4 times that needed to

control weedy *Poa* species in cool-season turf such as fairways, athletic fields, and lawns (Moghu 2016; Rana et al. 2015), are unlikely to cause injury soon after treatment regardless of Kentucky bluegrass variety.

There was a significant year-by-variety interaction ($P < 0.0001$) for Kentucky bluegrass injury I_{30} values at 6 MAIT and data are presented separately by year and variety (Table 1). The minimum methiozolin rate estimated to cause 30% Kentucky bluegrass injury was 4.5 and 3.7 kg ha⁻¹ in 2011 and 2013, respectively (Table 1). At 6 MAIT, visual symptoms of methiozolin phytotoxicity to Kentucky bluegrass were not evident but the injury was apparent as a decreased growth rate such that Kentucky bluegrass turf was slower to fill voids caused by dead weeds at higher methiozolin rates. Because all 110 Kentucky bluegrass varieties at 6 MAIT had I_{30} values of 3.7 kg ha⁻¹ or greater (Table 1), no concerns over using methiozolin on fairway-height Kentucky bluegrass are apparent, even when applied at more than twice the recommended weed control rate, which is 1 kg ha⁻¹ for annual bluegrass control (McNulty and Askew 2011; Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013). In preliminary research at Virginia Tech, methiozolin at 1 kg ha⁻¹ applied twice in the fall at a 2-wk interval controlled annual and roughstalk bluegrass greater than 92% with no injury to Kentucky bluegrass cv. ‘Midnight II’ at 6 MAIT (Rana et al. 2015).

Although methiozolin was generally safe for all Kentucky bluegrass varieties, the effects on varieties were dependent on year. Apparently, lower I_{30} values at 6 MAIT in 2013 compared with 2011 could have been from lower winter temperatures in 2013 (Table 2) that likely increased winter stress of Kentucky bluegrass and decreased Kentucky bluegrass growth rate. However, Shortell et al. (2009) did not observe a significant year-by-variety interaction when

evaluating the response of 55 Kentucky bluegrass varieties to bispyribac-sodium and indicated that varietal performance was under strong genetic control that was not highly affected by fluctuating environmental conditions. Although other researchers (Affeldt et al. 2008; Mueller-Warrant et al. 1997; Shortell et al. 2008) have found differential responses of Kentucky bluegrass varieties responses to the acetolactate synthase-inhibiting herbicides, primisulfuron and bispyribac-sodium, we did not observe any obvious trends in methiozolin effects on Kentucky bluegrass injury or I_{30} values from genetic variability among Kentucky bluegrass varieties (Table 1). For example, at 1.5 MAIT, the seven varieties that had I_{30} values lower than 4 kg ha⁻¹ represented five different genetic groups and none was among the lowest I_{30} values in 2013 (Table 1). In a study of nine bentgrass (*Agrostis sp.*) varieties maintained as putting green turf, only interspecific variability in bentgrass response to methiozolin was observed (Hoisington et al. 2014). Attempts to compare between Kentucky bluegrass genetic classifications statistically were unsuccessful because of disproportionate numbers of varieties in each classification. For example, several genetic classifications were represented by only one or two varieties, whereas while others contained as many as 25 varieties (Table 1).

Methiozolin rates influenced turf NDVI (Figure 1) and turf quality at 1.5 (Figure 2) and 6 MAIT (Figure 3) and these responses were dependent on methiozolin effects on weed populations (Figures 4 and 5). At 1.5 MAIT, the main effects of Kentucky bluegrass variety and methiozolin rate were significant for NDVI ($P < 0.0004$). In the interest of brevity, data are not shown for Kentucky bluegrass varieties but significant points will be discussed. When pooled over years and Kentucky bluegrass varieties, turf NDVI declined linearly with increasing methiozolin rates (Figure 1). Increasing methiozolin rates increased the speed and severity of

weed control, especially annual bluegrass which accounted for 25 to 50% of plot area depending on the year (Figure 4), and caused the concomitant decrease in turf NDVI (Figure 1). At 1.5 MAIT, annual bluegrass and other weeds were starting to become chlorotic; thus, the decline in NDVI was slight with a slope of 0.005 (Figure 1). Turf NDVI at 6 MAIT had a significant year-by-variety-by-rate interaction ($P = 0.0134$) and year-by-rate interaction ($P < 0.0001$). At 6 MAIT, turf NDVI decreased linearly in 2011 and exhibited a curvilinear response in 2013 (Figure 1). Winter conditions in 2013 were more severe than they were in 2011 (Table 2) which led to natural mortality of weeds in nontreated checks (Figure 4). The curvilinear response of NDVI by methiozolin rates in 2013 revealed improved Kentucky bluegrass cover at low rates of methiozolin compared with the nontreated checks (Figure 1). In 2011, NDVI in the nontreated turf was considerably higher because of increased weed cover compared with the 2013 (Figures 1 and 4). Turf color, percentage of live cover, and turf injury have been shown to be highly correlated with NDVI (Bell et al. 2002; Trenholm et al. 1999). Lee et al. 2011 reported higher mowing heights yielded higher NDVI compared with lower mowing heights and hybrid bluegrass species. This is due to a reflection of greater green leaf area and biomass at the high mowing height. Therefore, height reduction following methiozolin applications might have also contributed to lower NDVI values at higher methiozolin rates.

The Kentucky bluegrass variety main effect for NDVI (data not shown) was likely caused by differences in canopy characteristics such as leaf angle, leaf width, cell wall constituents, shoot water content, leaf turgidity, and canopy density among Kentucky bluegrass varieties as reported by other researchers (Berry et al. 1969; Brede and Duich 1982; Brosnan et al. 2005) and these differences have been shown to influence NDVI (Gausman 1977; Jensen 2007; Penuelas et

al. 1993; Stiegler et al. 2005; Trenholm et al. 2000). However, turf NDVI trends were not consistent within classification types (Table 1) in our study (data not shown) possibly because of variable weed density between plots. At 6 MAIT, methiozolin at 2 kg ha⁻¹ preserved or increased turf NDVI for 98 of 110 varieties in 2011 and all varieties in 2013 (data not shown).

Turf quality at 1.5 MAIT exhibited a year-by-variety-by-rate interaction ($P = 0.0002$) and a year-by-rate interaction ($P < 0.0001$), indicating that the effects of Kentucky bluegrass variety and methiozolin rate on turf quality were dependent on the year. In the interests of brevity, only data for the rate-by-year interaction are presented but both interactions of variety by rate by year and rate by year will be discussed. For both 2011 and 2013, turf quality followed trends similar to NDVI at 1.5 MAIT with quality decreasing with increasing methiozolin rates (Figures 1 and 2). Turf quality among Kentucky bluegrass varieties at 1.5 MAIT ranged from 4.33 to 7.25 in 2011, and from 4.68 to 6.98 in 2013, and did not exhibit clear trends associated with Kentucky bluegrass varietal classification (data not shown). At 6 MAIT, turf quality had a significant year-by-variety-by-rate interaction ($P = <0.0001$; data not shown) and a year-by-rate interaction ($P = <0.0001$; Figure 2). At 6 MAIT, methiozolin at 2 kg ha⁻¹ preserved or increased turf quality for all 110 varieties in both years (data not shown). Even at 4 kg ha⁻¹, methiozolin maintained or increased quality compared to the nontreated check of 106 varieties in 2011 and 93 varieties in 2013. However, in this study, nontreated checks had high weed pressure (Figures 4 and 5) leading to reduced quality. When averaged over Kentucky bluegrass varieties, turf quality at 6 MAIT exhibited a curvilinear response to methiozolin rates in both years (Figure 3) similar to the curvilinear response in turf NDVI that occurred in 2013 (Figure 1). In 2011, nontreated plots had greater weed pressure that increased NDVI but did not necessarily increase turf quality due

to variability in texture and color exhibited by weeds. Because of turfgrass quality is determined by several factors, including canopy density, texture, uniformity, color, and smoothness (Turgeon 1999), weeds can severely impact visual assessments of turf quality. The NDVI which is more correlated with turf color, the percentage of live cover, and chlorophyll content may not be negatively impacted by weeds (Bell et al. 2002; Stiegler et al. 2005).

Both intersects and slopes of Kentucky bluegrass percentage RCC regressed by methiozolin rates had a significant year-by-variety interaction ($P < 0.0001$) and variety means are presented separately by year (Table 1). In this case, intersect values approximate the percentage change in Kentucky bluegrass cover caused by treating plots with 2 kg ha^{-1} methiozolin. Intersects ranged from -9.3 to 689% in 2011, and 13.3 to 1022% in 2013 (Table 1). Thus, Kentucky bluegrass cover response from methiozolin applied at the low rate ranged from minimal effect to a 10-time improvement in Kentucky bluegrass cover (Table 1). Kentucky bluegrass cover in nontreated checks averaged 38 and 29% in 2011 and 2013, respectively (data not shown). Only two varieties, 'Everest' and 'Emblem,' in 2011 had a negative intersect value, indicating that methiozolin at 2 kg ha^{-1} decreased Kentucky bluegrass cover by 4.9 and 9.3%, respectively, but these values were not significantly different from zero (Table 1). Most of slope values were negative indicating that Kentucky bluegrass cover decreased with increasing methiozolin rates (Table 1). By controlling weeds, methiozolin at 2 kg ha^{-1} improved Kentucky bluegrass cover compared with nontreated check but as methiozolin rate increased beyond 2 kg ha^{-1} , weed control was more complete and Kentucky bluegrass appeared to be stunted such that recovery of voids left by dead weeds was slowed. For these reasons, the cover was generally highest at the 2

kg ha⁻¹ rate and declined with increasing rate but was still greater than the nontreated check, even at the highest rate in most cases (Table 1).

Evidence of weed control by methiozolin at 6 MAIT is shown in Figures 4 and 5. In the case of annual bluegrass, corn speedwell, parsley-piert, and Persian speedwell, the interaction of year by methiozolin rate was significant ($P < 0.0001$) and regressions explain the effect of methiozolin rate separately by year (Figure 4). In the case of mouseear chickweed, common chickweed, and hairy bittercress, only the rate main effect was significant ($P = 0.0021$), and data were pooled over years (Figure 5). In all cases except parsley-piert, increasing methiozolin rate caused a curvilinear or linear decline in weed cover (Figures 4 and 5). Annual bluegrass cover at the 2 kg ha⁻¹ rate indicates that methiozolin controlled annual bluegrass greater than 90% each year (Figure 4). On golf putting greens, methiozolin applied in fall at 0.5 and 1.0 kg ha⁻¹ controlled annual bluegrass more than 90%, 5 to 8 MAIT (Brosnan et al. 2013; Koo et al. 2014; McCullough et al. 2013; Moghu 2016; Xiong et al. 2015). There are no prior reports, to our knowledge, that indicate methiozolin may control certain winter annual broadleaf weeds following two fall applications. In the current study, methiozolin controlled five of six broadleaf weeds evaluated (Figures 4 and 5). In all cases where year interactions were significant, weed cover in the nontreated check and weed cover reduction by methiozolin were lower in 2013 compared with 2011. Colder winter temperatures in 2013 (Table 2) could have prevented or delayed germination of some weeds until later in the spring, thus allowing the weeds to avoid PRE control by methiozolin soon after fall applications. Methiozolin did not control parsley-piert regardless of application rate (Figure 4). Cover of this weed tended to increase as other formerly dominant weeds, such as annual bluegrass, were removed (Figure 4).

Results from this study indicate that methiozolin at 2 to 4 kg ha⁻¹ or lower will be safe on a broad range of Kentucky bluegrass varieties spanning the known genetic classifications. Two fall applications of methiozolin at 2 kg ha⁻¹ or greater can selectively control annual bluegrass and a variety of winter broadleaf weeds in fairway-height (1.5 cm) Kentucky bluegrass. More research is needed to evaluate weed control at lower methiozolin rates but a considerable margin of safety appears to exist for using methiozolin on Kentucky bluegrass.

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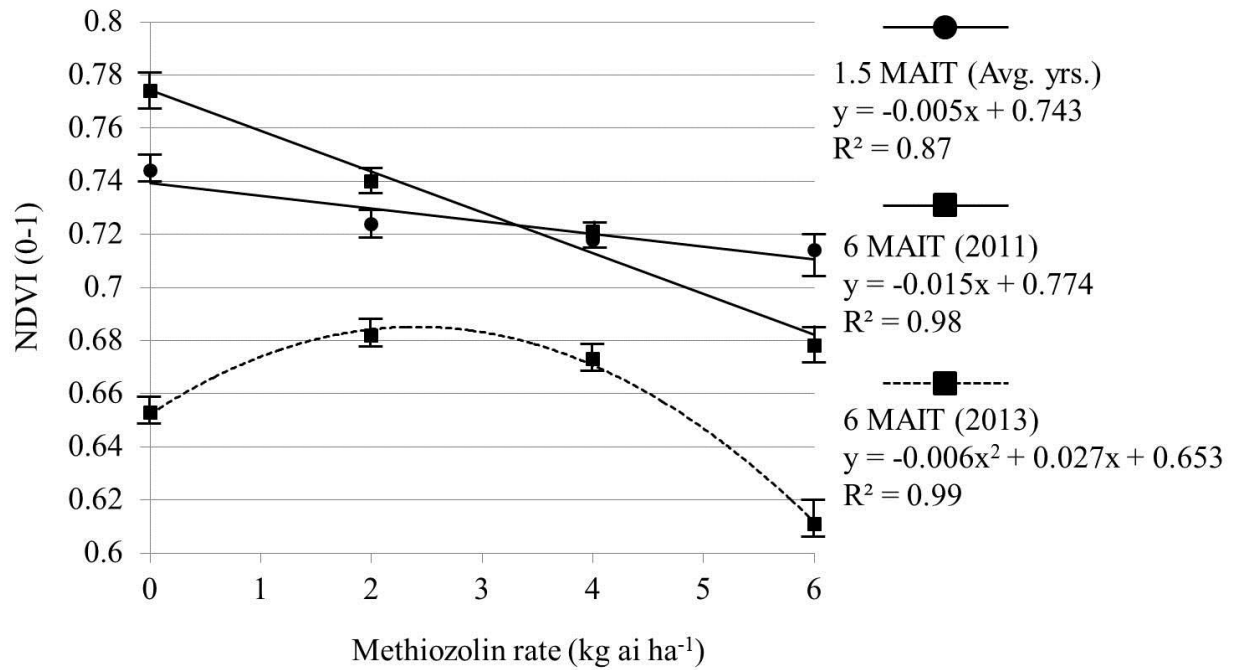


Figure 1. Main effect of methiozolin rate at 1.5 months after initial treatment (MAIT) and interaction of year-by-methiozolin rate at 6 MAIT for turf Normalized Difference Vegetative Index (NDVI), averaged over 110 Kentucky bluegrass varieties. Bars indicate 95% confidence interval.

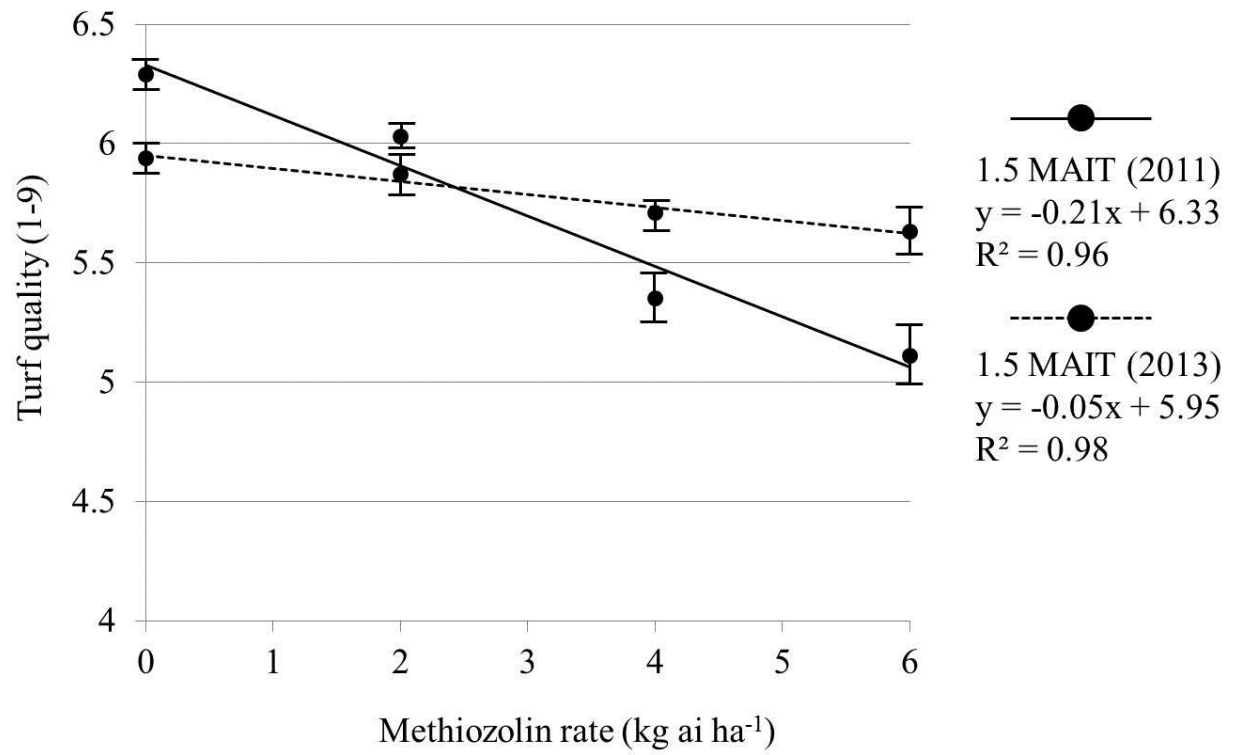


Figure 2. Interaction of year-by-methiozolin rate at 1.5 months after initial treatment for turf quality, averaged over 110 Kentucky bluegrass varieties. Bars indicate 95% confidence interval.

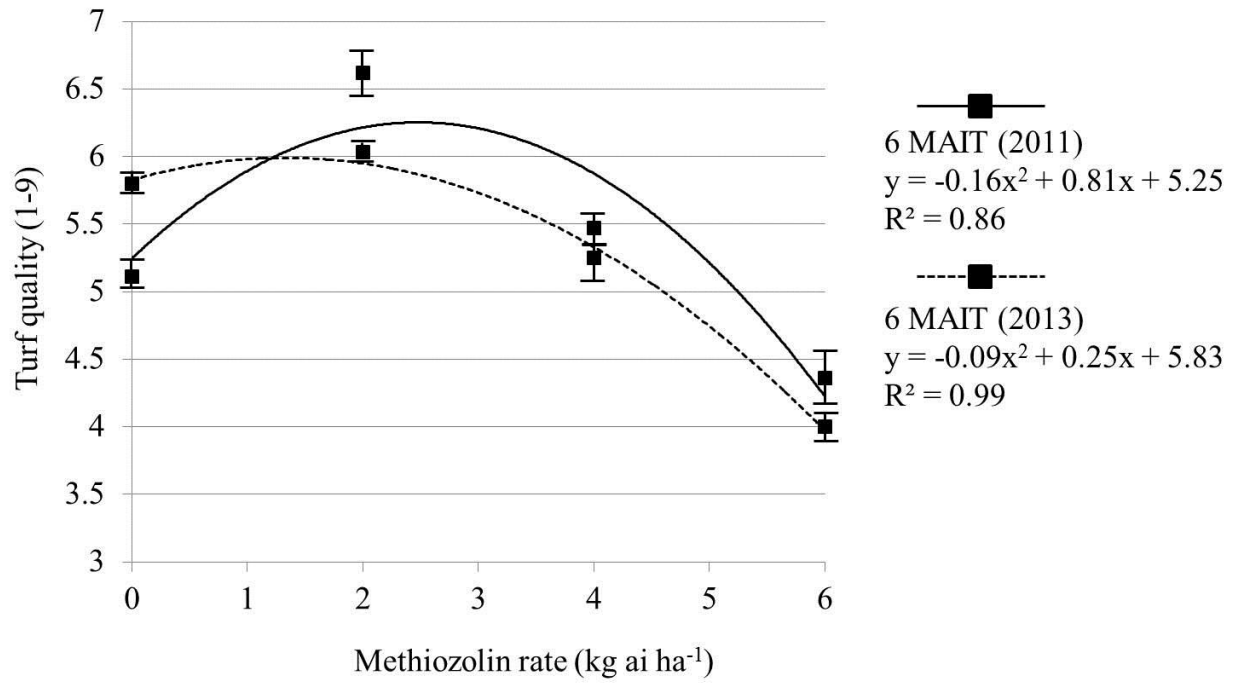


Figure 3. Interaction of year-by-methiozolin rate at 6 months after initial treatment for turf quality , averaged over 110 Kentucky bluegrass varieties. Bars indicate 95% confidence interval.

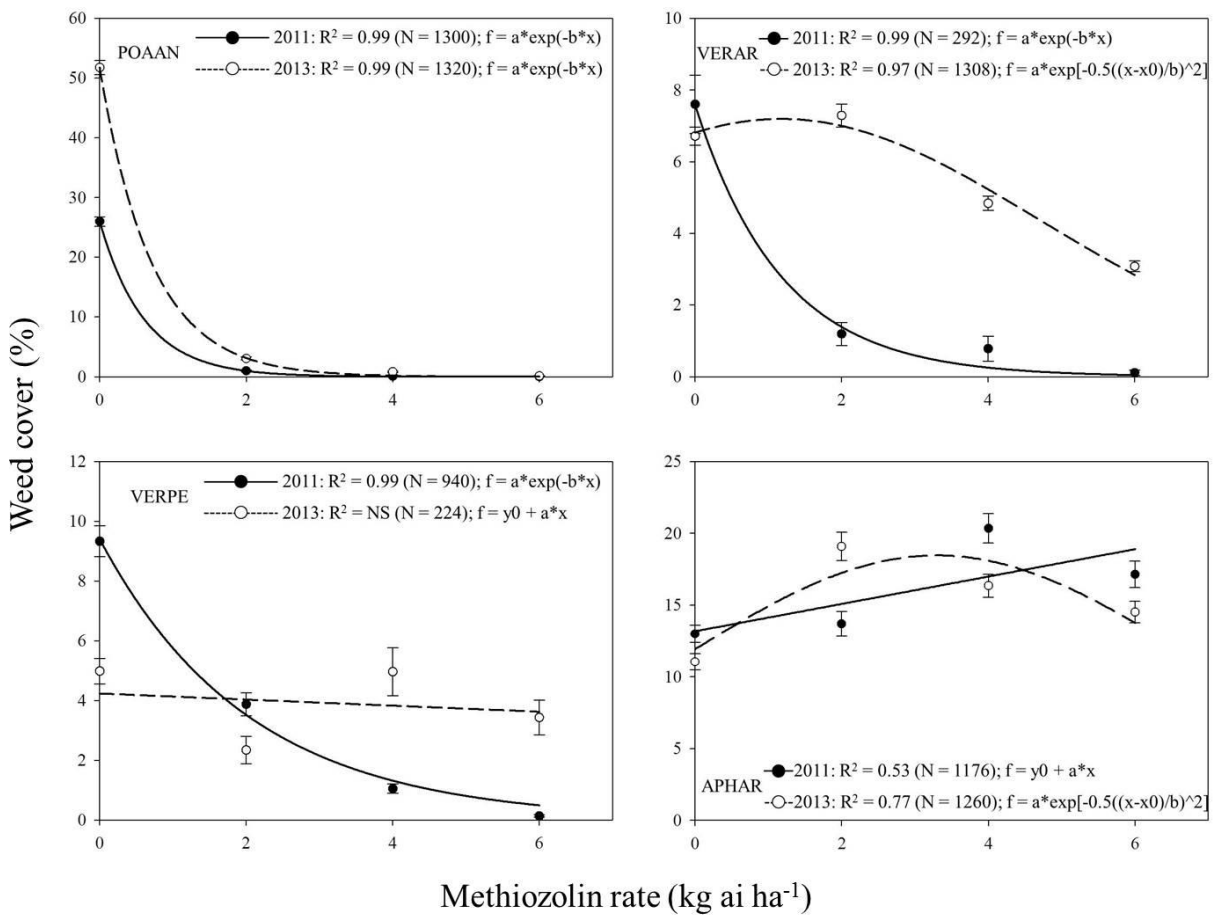


Figure 4. Interaction of year-by-methiozolin rate at 6 months after initial treatment for annual bluegrass (POAAN), corn speedwell (VERAR), Persian speedwell (VERPE), and parsley-piert (APHAR) cover. Bars indicate 95% confidence interval, N equals number of replications.

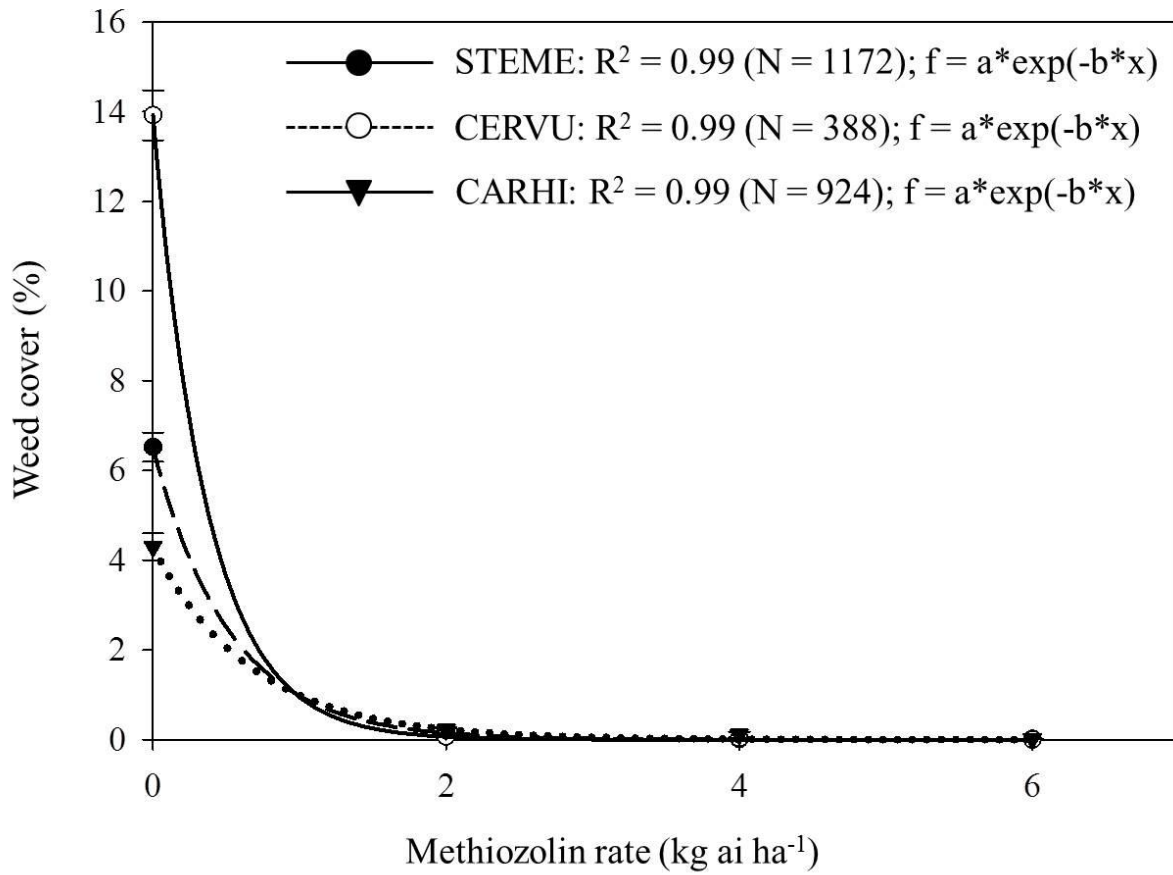


Figure 5. Main effect of-methiozolin rate at 6 months after initial treatment for mouseear chickweed (CERVU), common chickweed (STEME), and hairy bittercress (CARHI) cover. Bars indicate 95% confidence interval, N equals number of replications.

Table 1. Effect of year and Kentucky bluegrass variety on Kentucky bluegrass injury I_{30} values at 1.5 and 6 months after initial treatment (MAIT), and the intersect and slope of Kentucky bluegrass relative cover change (RCC) regressed by methiozolin rate at 6 MAIT following two fall applications of 2, 4, and 6 kg ai ha⁻¹ methiozolin at the Turfgrass Research Center in Blacksburg, VA.

POAPR ^a variety	Classification type ^d	I_{30} ^b				POAPR RCC ^a x rate 6 MAIT ^a			
		1.5 MAIT ^a		6 MAIT ^a		Intersect ^c		Slope ^c	
		2011	2013	2011	2013	2011	2013	2011	2013
		g ai ha ⁻¹				%			
Baron* ^e	BVMG ^a	8.04	5.41	5.59	5.87	94.1	683	-10.8	-101.4
Corsair*	BVMG ^a	8.62	5.98	5.28	4.68	77.6	255	-11.7	-31.0
A98-689	BVMG ^a	3.88	6.07	4.87	5.33	374	225	-32.2	-33.3
Rhapsody*	Compact	7.18	6.96	5.33	4.82	191	686	-37.4	-119.2
Avid*	Compact	3.77	5.63	5.55	4.84	219	439	-28.1	-63.6
Hampton*	Compact	6.16	7.21	5.11	9.55	59.5	13.3	-14.2	-2.00
Blueberry*	Compact	8.77	5.49	4.90	5.40	143	261	-16.7	-37.5
Pinot*	Compact	7.91	5.84	5.17	5.66	152	664	-25.7	-69.4

Shiraz*	Compact	-	6.39	5.56	4.73	96.3	345	-2.78	-67.3
Prosperity*	Compact	-	5.29	5.09	4.61	254	258	-30.1	-47.3
Skye*	Compact	5.80	5.83	5.62	6.84	229	626	-7.78	-8.33
Jump Start*	Compact-America	7.07	5.75	4.84	4.83	124	504	-17.8	-69.8
Futurity*	Compact-America	5.12	5.76	5.68	7.20	120	312	-12.2	2.08
Bewitched*	Compact-America	5.96	5.82	7.01	7.07	133	247	-0.21	-19.2
Empire*	Compact-America	-	5.45	5.04	4.71	303	128	-50.0	-24.8
Blue Note*	Compact-America	7.10	6.89	5.36	5.25	689	124	-133.7	-16.0
America*	Compact-America	-	6.28	7.15	5.53	134	350	-9.17	-31.5
Diva*	Compact-America	7.57	5.65	5.08	8.18	103	48.6	-16.2	-17.4
Dynamo*	Compact-America	4.07	5.97	5.06	6.23	441	335	-64.3	-6.25
Glenmont*	Compact-America	5.11	5.44	6.02	5.18	45.8	98.0	-16.2	46.7
Mystere*	Compact-America	8.33	5.63	5.42	8.21	83.7	629	-8.13	-9.52
Armada*	Compact-America	7.11	5.37	5.15	5.21	217	396	-28.5	-54.2
Moonlight SLT*	Compact-America	-	5.47	5.15	8.22	217	446	-7.42	-58.3

A00-1400*	Compact-America x Midnight	7.21	5.97	6.40	5.19	190	59.2	-9.10	-11.2
Noble*	Compact-America x Midnight	-	7.03	6.71	8.68	257	362	-24.4	-34.3
A00-247	Compact-America x Shamrock	6.35	6.10	5.18	6.71	262	343	-34.9	-21.4
Argos*	Compact-America x Shamrock	7.51	6.83	5.34	5.31	149	294	-20.5	-46.1
Full Back*	Compact-America x Shamrock	3.39	6.24	4.77	4.69	137	226	-12.9	-44.7
Award*	Compact-Midnight	-	6.16	6.93	5.28	63.9	363	-4.52	-41.7
Barrister*	Compact-Midnight	-	5.58	6.13	5.08	228	154	-10.0	-23.5
Beyond*	Compact-Midnight	8.60	5.68	5.84	6.18	68.3	127	-7.38	-22.0
Bluestone*	Compact-Midnight	10.21	5.92	22.38	5.20	45.6	110	5.96	31.7
Everest*	Compact-Midnight	-	6.85	10.18	5.75	-4.90	69.3	21.7	-1.11
Everglade*	Compact-Midnight	6.18	7.32	5.63	5.61	216	244	-13.1	-37.2
Excursion*	Compact-Midnight	-	6.51	7.04	6.98	107	126	-3.00	-1.94
Impact*	Compact-Midnight	-	8.52	6.04	8.88	182	68.3	-0.88	-9.03
Granite*	Compact-Midnight	-	6.22	6.89	6.16	218	187	-13.8	-13.0
NuChicago*	Compact-Midnight	3.82	6.81	5.82	6.13	291	420	-17.9	-48.5

Ginney II*	Compact-Midnight	4.96	6.25	5.26	6.24	232	56.0	-9.58	-8.68
Solar Eclipse*	Compact-Midnight	-	6.01	5.64	3.68	184	271	-21.8	-29.4
Alexa II*	Compact-Midnight	5.96	5.91	6.59	7.24	110	171	-5.83	15.8
4-season*	Compact-Midnight	7.22	5.74	4.51	5.71	304	120	-53.2	-19.6
Sudden Impact*	Compact-Midnight	5.63	6.17	6.14	6.59	133	218	12.9	-26.9
Midnight*	Compact-Midnight	4.96	6.52	5.67	9.55	112	192	-17.8	-1.94
Nu Destiny*	Compact-Midnight	6.18	6.97	7.89	6.93	94.9	620	0.00	-77.1
NuGlade*	Compact-Midnight	-	6.15	6.63	6.68	156	341	-9.58	-35.8
Rhythm*	Compact-Midnight	7.90	6.63	6.08	7.05	347	327	-7.39	-26.9
Rugby II*	Compact-Midnight	4.23	6.16	6.83	5.55	104	330	-7.24	-46.3
J-1334	Compact-Midnight	9.55	7.04	6.74	7.65	157	457	-15.5	10.1
J-2502	Compact-Midnight	-	5.72	6.10	5.56	212	143	-19.8	-19.2
J-3429	Compact-Midnight	5.96	5.48	5.44	4.75	105	129	7.04	-30.3
MSP 3723	Compact-Midnight	7.79	6.17	7.02	5.74	96.8	321	-13.0	-31.0
MSP 3724	Compact-Midnight	3.92	5.74	5.02	4.98	121	313	-18.7	-54.6

Barvette HGT*	Cynthia	5.66	8.03	-	7.27	16.8	96.0	-0.53	-7.85
H94-305	Eurasian	5.66	5.56	-	5.19	65.5	228	-8.76	-12.3
Kenblue*	Eurasian	6.36	6.72	5.55	4.71	40.6	44.4	-4.29	-10.0
Bariris*	High Density	-	5.61	7.05	4.56	66.5	1000	5.65	-151.4
Emblem*	High Density	-	5.63	5.71	4.41	-9.30	536	58.3	-102.2
Washington*	High Density	6.57	5.80	4.94	5.01	141	453	-19.9	-68.6
Washington II*	High Density	5.47	5.42	4.62	4.65	143	186	-20.8	-36.7
Juliet*	Julia	6.26	7.09	4.97	4.85	102	330	-21.6	-56.9
Julia*	Julia	6.45	5.88	4.94	5.26	143	275	-12.6	-39.7
Sombrero*	Limousine related	5.70	5.98	4.85	4.68	113	802	-0.69	-147.8
Harmonie*	Limousine related	5.52	5.72	5.10	4.80	199	171	-34.9	-35.3
Starburst*	Mid-Atlantic	-	6.64	6.01	5.55	37.0	283	-4.76	-37.2
A00-1254	Mid-Atlantic	-	6.43	5.68	10.79	60.0	27.0	-10.4	14.0
Aura*	Mid-Atlantic	4.98	5.96	5.54	5.73	49.4	439	-11.8	-40.8
Zinfandel*	Mid-Atlantic	-	6.06	7.04	7.64	122	555	-1.83	1.46

Touche'*	Mid-Atlantic	5.89	5.77	4.77	4.75	188	790	-25.7	-93.5
MSP 3722	Other	9.16	7.28	5.39	5.71	84.7	471	-2.92	-81.5
Rubicon*	Other	5.97	5.33	5.15	4.43	330	167	-49.0	-38.2
Arrowhead*	Other	5.69	5.77	4.70	4.52	314	279	-50.0	-53.6
A95-410	P-105 related	7.96	5.29	5.41	4.63	262	137	-14.9	-32.8
Aries*	Shamrock	5.88	5.91	4.89	4.64	118	91.1	-21.5	-21.2
Wild Horse*	Shamrock	7.88	5.73	4.89	5.98	343	70.3	-37.5	-19.9
Volt*	Shamrock	6.93	5.37	5.42	4.78	221	20.9	-42.4	-9.58
Gaelic*	Shamrock	5.78	6.04	4.61	4.43	221	194	-40.4	-49.4
Shamrock*	Shamrock	5.91	6.58	4.69	4.75	142	146	-24.3	-32.2
Reveille*	TXBa x KYBa Hybrids	5.25	5.23	5.05	4.93	360	425	-40.1	-73.3
Bandera*	TXBa x KYBa Hybrids	7.32	5.30	4.95	5.02	284	169	-23.6	-25.0
1QG-38	Unclassified	4.69	5.59	6.57	5.48	192	643	-15.2	-32.1
AKB449	Unclassified	-	5.15	5.46	4.84	134	589	-5.31	-98.6
BAR VV 0665	Unclassified	5.96	5.08	4.69	4.74	410	1022	-42.7	-100.0

BAR VV 0710	Unclassified	-	5.43	6.76	5.44	128	521	6.25	-90.4
Barduke*	Unclassified	5.96	5.62	5.52	4.89	325	88.9	-18.5	-25.9
BAR VV 9630	Unclassified	4.41	5.99	5.42	5.58	261	177	-27.8	17.2
Barrari*	Unclassified	6.18	5.16	5.99	4.88	265	319	-13.2	-41.0
BD-98-2108	Unclassified	6.98	5.82	4.55	4.96	315	232	-43.2	-39.0
Belissimo	Unclassified	9.03	5.84	6.80	7.01	157	284	-21.0	-16.5
Ravel 1	Unclassified	5.35	6.77	4.81	5.15	198	302	-29.4	-36.2
Greenteam	Unclassified	3.90	5.96	5.36	4.66	302	272	-20.6	-49.0
CPP 822	Unclassified	4.47	5.47	5.79	4.79	119	405	-11.5	-68.0
DLF 76-9075	Unclassified	6.74	5.64	4.61	4.97	163	206	-19.1	-29.2
DP 76-9066	Unclassified	8.11	6.44	5.82	7.13	332	114	-8.99	-10.6
Mermaid	Unclassified	-	9.83	6.58	4.71	69.7	91.8	-9.20	-26.5
H98-701	Unclassified	5.96	5.70	6.52	5.59	78.9	564	-3.67	4.17
Gladstone*	Unclassified	6.65	5.45	4.97	4.52	140	429	-10.6	-83.6
Aviator*	Unclassified	8.00	5.78	5.61	5.00	166	229	-30.7	1.19

Yankee*	Unclassified	6.56	6.02	4.73	4.94	141	309	-27.1	-47.2
POPR 04594	Unclassified	6.09	5.37	5.66	5.27	73.4	690	-5.79	-102.6
PSG 711	Unclassified	7.99	5.97	6.13	5.20	171	572	-6.45	-23.3
PST-101-73	Unclassified	-	6.19	6.07	5.36	101	235	-2.96	-24.1
PST-1A1-899	Unclassified	-	5.65	5.19	5.40	182	216	-9.72	-36.9
Madison*	Unclassified	3.80	5.33	5.77	4.75	203	193	25.0	-43.6
RAD-504	Unclassified	-	5.09	6.83	4.64	34.8	549	-3.38	-95.6
RAD-762	Unclassified	6.52	5.85	4.82	4.67	106	110	-18.2	-25.5
SPTR 2959	Unclassified	7.06	5.47	5.00	4.76	140	322	-13.1	-61.8
STR 2485*	Unclassified	6.49	6.07	4.91	4.93	246	578	-26.4	-50.9
STR 2553	Unclassified	6.55	5.51	5.47	5.68	229	420	-14.7	-53.3
SW AG 514	Unclassified	8.83	6.83	5.22	5.09	124	171	-22.6	-7.29
LSD		2.17	0.80	1.70	1.59	286	617	49.2	90.4

^a Abbreviations: BVMG = Baron, Victa, Merit, Gnome types; MAIT: Months after initial treatment; POAPR = Kentucky bluegrass; RCC = Relative Cover Change; TXB = Texas bluegrass.

^b Kentucky bluegrass injury I_{30} values refer to methiozolin rate needed to incite 30% injury to Kentucky bluegrass. Kentucky bluegrass injury at 1.5 and 6 MAIT was visually estimated on a 0 to 100% scale based on an estimation of the reduction in green tissue, resulting from Kentucky bluegrass discoloration, stunting, and stand reduction compared to nontreated check, where 0 is no injury, 30% is maximum acceptable injury, and 100% is complete loss of all green foliage. I_{30} values were calculated by first regressing Kentucky bluegrass injury against methiozolin rates using the exponential equation $y = a^x$; where y is KY bluegrass injury, a is an estimated parameter that determines the rate of injury increase, and x is methiozolin rate and then entering 30% injury for y and solving for x on each variety main plot in each year. Data were separated by year and Kentucky bluegrass variety because of significant ($P < 0.0001$) year-by-variety interaction.

^c Intersect of Kentucky bluegrass cover change refers to percent change in Kentucky bluegrass cover at 2 kg ha^{-1} of methiozolin. The slope of Kentucky bluegrass cover change refers to percent change in Kentucky bluegrass cover with each 1 kg ha^{-1} increase in methiozolin rate. Kentucky bluegrass cover was visually estimated as percent green cover in a methiozolin rate sub-plot. Kentucky bluegrass cover change for each subplot was calculated as percent change in Kentucky bluegrass green cover in treated subplot compared to nontreated check sub-plot in the corresponding variety main plot. Intersect and slope were calculated by linear

regression. Intersect and slope were separated by year and Kentucky bluegrass variety because of significant ($P < 0.0001$) year-by-variety interaction.

^d Others and unclassified refer to Kentucky bluegrass varieties that are either intermediate in performance to two or more of the major types listed in the table above or have not been classified into different types.

^eA * indicates classification types of Kentucky bluegrass varieties in the above table are adopted from Honig 2011, Park et al. 2010, Shortell et al. 2009, and by personally contacting breeders and researchers from the concerned agencies.

Table 2. Monthly average temperature and rainfall during trial periods initiated in 2011 and 2013.

Month	Average temperature ^a		Average precipitation ^a	
	2011-12	2013-14	2011-12	2013-14
	C		mm	
October	11	12	75	67
November	8	4	94	76
December	4	3	92	134
January	2	-3	53	42
February	3	1	89	101
March	11	4	81	57
April	12	12	122	105
May	18	17	96	68

^a Temperature and precipitation data for a given year were accessed from online weather information website - wunderground.com.