EFFECT OF FOUR CREEPING BENTGRASS CULTIVARS AND QUANTIFIED FOOT TRAFFIC ON THE INVASION OF ANNUAL BLUEGRASS INTO A PUTTING GREEN

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ABSTRACT

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Research was conducted to determine the relationship between creeping bentgrass shoot density and the invasion of annual bluegrass (*Poa annua* L.) and determine the effect of foot traffic on annual bluegrass invasion. Putting green plots were seeded with Penncross, Providence, Penn G-2, and Bengal on 30 May, 2003. Annual bluegrass centers were counted in each plot seven times from 23 September, 2003 to 28 September, 2004. Creeping bentgrass shoot unit area^{-1} were measured once in October, 2004. An observational study was conducted to determine the amount of traffic placed on a putting green and its variability as daily pin placements are moved. Because pins are traditionally moved daily, any one area on a putting green only receives large amounts of foot traffic one day out of the week as observed in this study. Foot traffic was applied to the aforementioned creeping bentgrass plots as if each plot was a 2.6 m^2 area of a putting green and the pin was rotated daily. By 6 July, 2004, the accumulation of foot traffic significantly increased the invasion of annual bluegrass. The addition of foot traffic did not significantly affect creeping bentgrass densities. Penncross possessed the lowest shoot density of the cultivars, although the number of annual bluegrass centers was equal or more abundant in Providence, Penn G-2, and Bengal than Penncross on every rating date, except for 7 April, 2004. Creeping bentgrass shoot densities did not affect the rate of annual bluegrass invasion in this research.

To Jettie and Alenna, for your love and support.

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Chapter 1

A Putting Green Traffic Methodology for Research Applications Established by In Situ Modeling

INTRODUCTION

Though golf greens are now constructed to alleviate the effects of traffic, there is no question that increased play continues to affect the health of turfgrass. Any researcher that presented research regarding putting greens invariably hears the question, "did you apply traffic?" Unfortunately, often times, the reply is "No" due to the fact that there is no consensus on the best way to apply simulated traffic to putting green studies.

Over the decades there have been numerous studies that have reported or, at least, employed many different traffic applications to research putting greens. The sheer numbers of footsteps a golf green incurs every day has impacted the development of machines to simulate traffic for researchers in an efficient manner (Canaway, 1990; Dudeck and Burt, 1975; Kohlmeier and Eggens, 1983; Murphy et al., 2000; Neylan and Robinson, 1999; Shearman, 1989; Trenholm et al., 2001). There has been a variety of human foot traffic techniques employed for putting green traffic simulation as many golf spike studies and energetic researchers have worked to develop new strategies, whether the traffic is counted in minutes or in traverses (Brahler et al., 2001; Ferguson, 1958; Ferguson, 1959; Grau and Ferguson, 1948; Hall et al., 2001; Hamilton et al., 1997; Rose-Fricker et al., 1999). Many researchers, though, have not specified the exact amount of footsteps, minutes, or traverses applied to their plots, rather reported that they have trafficked a typical amount (Torello et al., 1997).

General ideas of putting green traffic application and simulation are numerous, however, other ultra-specific observations about putting green traffic are found. A common referenced article (Gibeault et al., 1983) for traffic application cites the observations of Charles Cogan, Green Committee chairman at Irvine Coast Country Club, California who explains:

> The average golf shoe has 12 spikes; i.e., 24 spikes per golfer. I have found golfers take an average of 26 full steps (52 paces) per green. Therefore, each golfer leaves (26 x 24) 624 spike marks on each green. On 18 greens, he leaves 11,232 spike marks. If there are 200 rounds of golf played a day, there are 2,246,400 spike marks left behind. If this goes on for 30 days, you have 67,392,000 spike marks per month. And now, you wonder why you can't sink a putt?

In Putt Like the Pros, Pelz (1989) reports on his observation of a foursome leaving behind more than 500 footsteps on a putting green as they entered, putted, and exited. That is an average of 125 footsteps per golfer. These observations show that much variation should be expected when counting footsteps on putting greens—there is no universal number.

An obvious, yet important, observation was made while trafficking putting greens long ago. Ferguson (1959), reporting on two golf-shoe sole studies, concluded that "frequent changes of cup locations and tee markers is extremely important." Observations like these helped to transform the maintenance and cultural practices on putting greens. It is now common practice to rotate pin locations on a putting green to disperse foot traffic.

There is much confusion and discussion about traffic methods and amounts of traffic adequate for traffic simulation on putting green research plots. The objectives of this observational study were a) to determine the relationship between putting green traffic and daily cup rotation on a putting green and b) to explore and present a new method of putting green traffic simulation.

MATERIALS AND METHODS

An observational trial was conducted on 3 June, 2003 at Forest Akers West Golf Course on the 13th green at Michigan State University in East Lansing, MI. During a golf outing, golfer's footsteps were systematically counted as they walked onto the putting green, made their putts, and walked off of the green. Golfers were coming through the course as foursomes.

Six sets of two concentric circles were "etched" into the green, representing six different pin placements for six different days of the week. The circles were made using a wire brush measuring 1.3 cm wide, scuffing the turf in such a manner that the golfers did not easily notice the circles. Each set of circles represented a different pin placement. The outside circle measured 1.5 m^2 while the inside circle measured 1.2 m^2. The sets of circles were placed in six different sectors on the putting green, each sector representing a different day in the pin rotation.

Footsteps were counted by two observers standing near the green as golfers entered the green, putted, and exited the green. Any portion of a shoe entering any part of the circle was counted as a footstep, and footsteps in the outer and inner circles were counted separately. The golfers were playing traditional golf, not a scramble or best ball competition. Over the course of the data collection, 78 individual rounds of golf were played.

Foot traffic is applied to a green by golfers in relation to a particular pin placement on a particular day. Pins are generally moved daily, or moved six times per week, as some golf courses close for one day a week. The majority of the foot traffic moves daily with the movement of the pin. Thus, the number of footsteps counted in each set of circles simulated the amount of traffic placed on one specific area on a putting green over an average week of play. This specific area is assumed to be congruent with all other equal areas on the putting green and is, therefore, one sample representing the putting green as a whole.

RESULTS AND DISCUSSION

The trial showed that foot traffic on a putting green is highly variable as the pin placement is changed. One specific area on a green, assuming pins are moved six days a week, only receives major amounts of foot traffic on the day that the pin is placed in that vicinity.

The concentration of foot traffic on a golf putting green is highly variable as golfers generally enter a green where they park their carts or drop their bags and exit in the same area as they return to those carts or bags, which directly relates to the location of the ensuing tee. It would be expected that foot traffic would be most concentrated around the cup or pin placement that day. Therefore, most putting greens have one area that generally receives the most entrance and exit traffic, which indicates that not all of the traffic is necessarily relative to the pin placement, but, certainly, most of the traffic, according to our observations, is related to the placement of the pin.

It is not a revelation that 70% of the footsteps (Table 1) were placed around the actual pin placement, but the data does remind us why superintendents rotate the pin placements daily. This data (Table 1) provide researchers a basis for the amount of footsteps or traffic to apply to putting green research plots and shows researchers that simulated putting green traffic should be rotated in the same manner a pin is rotated on a putting green. Just as traffic has a profound negative effect on the health of turfgrass, recovery time because of pin rotation has a profoundly positive effect on the health of turfgrass and should be expressed when applying traffic to putting green research plots.

Table 1. Count and distribution of footsteps for six pin placements after 78 rounds of golf on a putting green.

Simulated Placement	Distance from Pin (m)	Number of Footsteps		Distribution of Footsteps (percent)
		Inner Circle	Outer Circle	Both Circles
1	12	0	0	0
2	14	7	10	5
3	18	5	10	3
4	14	13	19	8
5	8	22	44	14
Pin		106	184	70

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Chapter 2

Effect of Creeping Bentgrass Cultivar and Traffic on Shoot Density and Annual Bluegrass Invasion

INTRODUCTION

Annual bluegrass (*Poa annua* L.) is often a part of putting greens whether it is welcomed or shunned. Golf course superintendents are forced to deal with color mottling as annual bluegrass interacts with creeping bentgrass (*Agrostis palustris* Huds.) and massive amounts of seedheads in late spring. Annual bluegrass and creeping bentgrass are turfgrass species that act very differently in putting green settings. When managing both species, golf course superintendents must also learn to manage different disease tolerances and nitrogen requirements. Beard (1970) stated that there are two approaches to the encroachment of annual bluegrass: control by cultural and/or chemical means or adoption of cultural practices to maintain annual bluegrass.

Preemergence and postemergence annual bluegrass herbicides are constantly being introduced and tested for use on putting greens. Chemicals have been tested as far back as the 1930s when lead arsenate emerged as an effective annual bluegrass herbicide (Sprague et al., 1937). Though many herbicides, such as bensulide, paclobutrozol, flurprimidol, and, recently, bispyribac sodium have proven useful for annual bluegrass control in creeping bentgrass putting greens, annual bluegrass often returns, making these herbicides short term control devices even when they work well.

Beard et al. (1978) stated that annual bluegrass occurrence in turf is due to reduced competition from the permanent turfgrasses and favorable conditions for annual bluegrass during at least a portion of the growing season. Beard et al. (1978) continued, stating that this reduced competition is usually caused by close mowing, excessive irrigation, poor drainage, compacted soils, intense traffic, improperly timed soil cultivation and vertical mowing, and/or use of non-adapted species or cultivars. The aforementioned are often inherent characteristics of putting greens, which, in part, explains why annual bluegrass is such an accomplished invader of putting greens.

Watschke and Schmidt (1992) stated, "most often the turfgrass community is composed of a poly-stand of species that are competing for light, water, nutrients, carbon dioxide, oxygen, and space. Seasonal growth patterns, growth habit and rate, and stress tolerance influence the competitive ability of each species."

Sprague and Burton (1937) did some of the first work with different strains of creeping bentgrass and their relative abilities to resist the infestation of annual bluegrass. Seaside, Virginia, Metropolitan, and Washington creeping bentgrasses were evaluated. They concluded that the density of the turf was "a controlling factor in determining the abundance of *Poa annua*." A dense stand of turfgrass, whether a golf course green or a home lawn, is more able to compete with weeds, such as annual bluegrass, for water, nutrients, and sunlight (Beard, 1973).

The first seeded variety of creeping bentgrass, Seaside, was released in 1923 and was said to have a medium shoot density (Beard, 1973). Great improvements were made in terms of adaptation, disease resistance, and shoot density when Penncross was released in 1954 (Beard, 1973; Musser, 1962). Providence followed Penncross and also became a widely used cultivar because of its improved dollar spot resistance and many other cultivars followed in time. As putting green heights continued to decrease, the need for creeping bentgrass varieties able to produce dense stands at low heights increased.

The Penn A- and G-series cultivars were developed with much higher shoot densities and are often advertised, specifically, to resist annual bluegrass invasion. The Penn A- and G-series are now commonly referred to as high shoot density cultivars relative to older cultivars or standard cultivars. Vargas and Turgeon (2004) separated creeping bentgrass cultivars for putting greens into three categories: low-density (600 to 900 shoots dm^{-2}), including Penncross, medium-density (1200 to 1600 shoots dm^{-2}), including Pennlinks, Providence, Putter, and L-93, and high-density (2200 to 2800 shoots dm^{-2}), including the Penn A- and G-series creeping bentgrasses. As research moved to improving shoot densities of new creeping bentgrass cultivars, new studies surfaced testing these new cultivars and their abilities to form dense putting green surfaces as a result of different management strategies.

Generally, a turfgrass with a higher tillering capacity has a better competitive advantage over a pest such as annual bluegrass (Danneberger, 1993). However, this tillering capacity is not always fully expressed (Danneberger, 1993). Lush (1988) showed that the tillering capacity of annual bluegrass exceeded that of creeping bentgrass from the end of autumn to the end of spring, while the tillering capacity of annual bluegrass was fully expressed. In contrast, creeping bentgrass became the dominant species in the putting green near the end of spring because its tillering was fully expressed and dominant relative to annual bluegrass. So, as creeping bentgrass cultivars are continually bred with larger tillering capacities, these capacities may not be fully expressed depending on controllable and uncontrollable aspects. Furthermore, researchers may never develop a creeping bentgrass cultivar with a tillering capacity comparable to that of some greens-type, high tillering annual bluegrasses when they are fully expressed.

Since 1999, six experiments, reporting actual shoot densities of new and old creeping bentgrass cultivars, have been published (Beard et al., 2001; Croce et al., 1999; Guertal, 2004; Jordan et al., 2003; Sifers et al., 2001; Sweeney et al., 2001).

Table 2 shows the shoot density results in shoots dm^{-2} from these experiments. Although shoot densities from each experiment were affected by different factors, the large variability between experiments, locations, and years are indicative of the sensitivity of creeping bentgrass shoot densities to many different factors. These experiments have set out to find and measure these sensitivities (Beard et al., 2001; Croce et al., 1999; Guertal, 2004; Jordan et al., 2003; Sifers et al., 2001; Sweeney et al., 2001).

Beard et al. (2001) compared high shoot density cultivars separately from standard cultivars as there is definite separation between the two classes. After three sampling dates (Table 2), Penn G2 averaged 2344 shoots dm^{-2}, Providence averaged 1656 shoots dm^{-2} and Penncross averaged 1369 shoots dm^{-2} (Beard et al., 2001). Sweeney et al. (2001) also found the Penn A- and G-series cultivars to have greater shoot densities than the standard cultivars. These six experiments (Beard et al., 2001; Croce et al., 1999; Guertal, 2004; Jordan et al., 2003; Sifers et al., 2001; Sweeney et al., 2001) repeatedly ranked Penncross in the least dense category and it was clear that the Penn A- and G-series creeping bentgrasses consistently produced denser stands of turf than the standard cultivars in any situation.

Jordan et al. (2003) found that shoot density can be increased by increasing the time interval between irrigation events. Sifers et al. (2001) found there was a general

Table 2: Adapted from six separate trials reporting creeping bentgrass shoot densities (shoots dm^{-2}).

Creeping Bentgrass Cultivar	Beard et al., 2001			Sifers et al., 2001		Sweeney et al., 2001			Jordan et al., 2003				Guertal, 2004	Croce et al., 1999		
	Sep 1995	Sep 1997	Sep 2000	May 1996	Oct 1996	Apr 1998	Jul 1998	Oct 1998	Jun 1997	Aug 1997	Jun 1998	Aug 1998	Jun 2001	Sep 1993	Sep 1994	Sep 1996
Penncross	1358	1631	1119	1369	1603	1092	1593	1133	1490	2150	2490	3150	510	1022	987	1642
Pennlinks	1553	2186	1431	1353	1533									1504	1301	1793
Providence	1395	2080	1494			1225	1424	1406						1425	1093	1799
L-93									1920	2960	4250	4470	570			
Penn A1	2325	2868	2175	3134	2767	1614	1496	1503						2240	1540	2656
Penn A2						1564	1981	1658					700			
Penn A4						1747	1791	1699		2420	3820	4410				
Penn G1	2228	2675	1772			1600	1595	1496					680	2612	1902	2912
Penn G2	2366	2725	1941	3547	3313	1554	1669	1609					630	2546	1793	2225
Penn G6	2700	3003	2199	3304	3046	1692	1816	1747					700	2378	1306	2662
Time: Seeding-Sample (mo)	40	64	100	32	37	21	24	27	7	9	19	21	45	4	16	40
Nitrogen	Mar-Oct: 37.5 kg ha^{-1} mo^{-1}			300 kg ha^{-1} yr^{-1} applied 10x		Jul '97-Aug '98: 25-37 kg ha^{-1} mo^{-1}			Oct-Dec: 32.7 kg ha^{-1} 2 wk^{-1} Mar-Jun: 12.2 kg ha^{-1} 2 wk^{-1}				0.1 kg ha^{-1} mo^{-1}	93-'94: 175 kg ha^{-1} yr^{-1} growing mo^{-1} 95-'97: 300 kg ha^{-1} yr^{-1} applied 8x (Mar-Oct)		
Height of Cut (mm)	3.2			3.2		3.1			4				4	5 ('93-'94); 4 ('96)		
Core Cultivation	None			2x yr^{-1}		None			None				Oct yr^{-1}	None		
Hydro-ject (high-velocity water injection)	None			None		None			None				May, Jun, Jul yr^{-1}	None		
Vertical Mowing	None			None		None			None				Sep, Dec, Feb yr^{-1}	None		
Topdressing	1x 2 mo^{-1}			4x yr^{-1}		1x 3 wk^{-1}			Occasional				Sep, Dec, Feb yr^{-1}	1x 2 mo^{-1}		
Site	Torino, Italy			Rolesville, NC		Dublin, OH			College Station, TX				Auburn, AL	Torino, Italy		
Traffic	None			None		None			None				None	None		

decline for most creeping bentgrass cultivars after a humid-hot stress period, except for Penncross, Seaside II, and Pennlinks, suggesting better adaptation to summer heat stress condition. Because these cultivars' characteristics, such as shoot density, are differentially affected by so many factors, known and unknown, it is difficult to compare those cultivars and their characteristics when measuring their relative abilities, such as competitiveness.

Two of the aforementioned studies included annual bluegrass invasion data along with shoot density data (Beard et al., 2001; Croce et al., 1999). Beard et al. (2001) transplanted annual bluegrass plugs into the existing creeping bentgrass cultivars and measured the creeping bentgrass shoot invasion or the outward annual bluegrass shoot encroachment. This assessment, although very reliable for vegetative encroachment, does not necessarily represent a cultivar's ability to limit annual bluegrass germination or seedling survival within the creeping bentgrass stand. Beard et al. (2001) found that the use of high shoot density cultivars does improve a putting green's ability to withstand annual bluegrass invasion. More specifically, Beard et al. (2001) found that those cultivars with densities above 2000 shoots dm^{-2} exhibited the most competitiveness in the suppression of annual bluegrass in a putting green. Croce et al. (1999) assessed annual bluegrass invasion visually and found that those creeping bentgrass cultivars with higher shoot densities were, generally, less prone to annual bluegrass invasion. The lowest ranking cultivars, in terms of annual bluegrass invasion, were the oldest cultivars (National, Emerald, Seaside, Astoria). Like Beard et al. (2001), Croce et al. (1999) found the Penn A- and G-series cultivars to rank the lowest in annual bluegrass invasion.

Turgeon (2002) conducted an experiment comparing ten annual bluegrass selections. They were plugged into three creeping bentgrass cultivars, Penn A-4, Penncross, and Pennlinks at fairway and putting green heights. Under the fairway-type culture, each of the annual bluegrass selections was overgrown by all of the creeping bentgrass varieties within the first year. At greens height, though, most of the annual bluegrass selections persisted with the creeping bentgrass varieties varying in competitive ability. Penn A-4 was most effective in restricting the growth of annual bluegrass. Turgeon reported, while the annual bluegrass plugs generally increased in size, they appeared to retreat in the summer months and expand in the winter months.
Murphy et al. (2000), in an experiment comparing fifteen creeping and velvet bentgrasses, also found that high density cultivars exhibited improved ability to resist annual bluegrass encroachment as opposed to older cultivars even under a range of traffic conditions.

Foot traffic on a putting green causes wear on the turfgrass and compaction on the soil. For recreational turfgrass, it is common that wear and compaction occur at the same time, but one or the other is normally the predominant stress (Carrow and Wiecko, 1989). It is intuitive that wear would be the primary stress of traffic on sandy soils and, conversely, soil compaction would be the main stress on soils high in silt and clay (Carrow and Wiecko, 1989). Wear is tolerated and resisted on different levels for different turfgrass species and different cultivars within species. Likewise, different turfgrass species and cultivars have different tolerances for soil compaction.

Annual bluegrass has a profound ability to persist in compacted soils. Creeping bentgrass, on the other hand, has a very low compaction tolerance making soil compaction, caused by daily traffic and mowing, a significant factor in the encroachment of annual bluegrass into creeping bentgrass putting greens (Beard, 1970). Since golf course superintendents use sand topdressing, core cultivation, and other methods to prevent and alleviate compaction, creeping bentgrass is not usually impeded by soil compaction in putting greens.

Wear injury incurred by turfgrasses from foot traffic is marked by abrasion, tearing, and stripping of leaf tissue, resulting in chlorophyll degradation and subsequent reduced photosynthesis (Trenholm et al., 2000). Wear injury can also leave turfgrasses more susceptible to insect and fungal attacks. Lush (1990) concluded that above-ground biomass is a more useful indicator of wear tolerance than shoot density. The power or self-thinning rule states that shoot density increases at the expense of canopy biomass (Lush, 1990). Sifers et al. (2001), when comparing twelve creeping bentgrass cultivars at greens height, found that those cultivars with higher or lower shoot densities did not necessarily have lower or higher shoot/mat/thatch dry weights, respectively.

However, Trenholm et al. (2000) observed increased wear tolerance of seashore paspalum (*Paspalum vaginatum* Swartz) cultivars with greater shoot densities, stating that it could have been due to the greater number of meristematic growth points and, therefore, inherent growth rate. So, although high shoot density creeping bentgrass cultivars may have decreased wear tolerance, relative to lower shoot density cultivars, their ability to recover from wear injury may be greater and may even be a larger asset in wear tolerance as a whole.

Murphy et al. (2000) included wear and compaction separately when studying the population dynamics of creeping bentgrass and annual bluegrass in a putting green. In preliminary results, they found that high density turfs, including Penn A-4 and some velvet bentgrass cultivars, showed good to excellent tolerance to wear and compaction treatments and showed excellent resistance to annual bluegrass encroachment under traffic conditions on a sandy loam soil. Murphy et al. (2000) also found that wear was more detrimental, in terms of population, for some bentgrass cultivars than others. Rose-Fricker et al. (1999) conducted a study comparing wear tolerances of twelve creeping bentgrass cultivars in a putting green to foot traffic with alternative golf shoes. They concluded that metal spikes inflicted the most damage and the denser creeping bentgrass cultivars, including many of the Penn A- and G-series cultivars, showed less damage initially when trafficked with the metal spikes. Penncross, though incurring more damage, had the quickest recovery from browning during the summer test.

Wear from foot traffic affects annual bluegrass and creeping bentgrass in many of the same ways, but wear also provides opportunity for the annual bluegrass population. Ball marks and spike marks can reduce creeping bentgrass competition for light by creating voids and exposing soil. In soils with large annual bluegrass seed-banks, these voids are often filled by germinating annual bluegrass plants. Those soils with small annual bluegrass seed-banks may be stocked by seed on soles of shoes or on any machine that is contaminated. Since annual bluegrass can seed even at a cutting height of 3 mm, putting green soils are always receiving contributions, either from annual bluegrass plants or seeds brought in from other areas of a golf course. When voids are formed, the race to fill that void by annual bluegrass or creeping bentgrass is affected by many different factors. Once annual bluegrass seed germinates in putting greens, it is well suited to compete with the surrounding plants because annual bluegrass has been shown to have the highest relative seedling growth rate when compared to 132 other species (Grime and Hunt, 1975).

The objectives of this research were a) to evaluate the effect of foot traffic on the shoot densities of four creeping bentgrass cultivars and b) to determine the effects of four creeping bentgrass cultivars with varying shoot densities maintained with and without traffic on the invasion of annual bluegrass into a putting green.

MATERIALS AND METHODS

Research was initiated in 2003 at the Michigan State University Hancock Turfgrass Research Center (HTRC) in East Lansing, MI. The site was maintained for ten years as an annual bluegrass (*Poa annua*) fairway ensuring a large soil seed-bank of annual bluegrass seed. This turf and thatch were stripped with a sod cutter and on 30 May, 2003 an 18.3 x 18.3 m putting green was established in its place. The soil type is an Aubbeenaubbee-Capac sandy loam.

The study was designed as a two-factor split-plot design with four replications. The main factor consisted of four creeping bentgrass (*Agrostis palustris* Huds.) cultivars: Penncross, Providence, Penn G-2, and Bengal. The second factor consisted of two levels of traffic: traffic and no traffic.

Each main plot, measuring 3.3 x 1.6 m, of the putting green was seeded at 48.8 kg pure live creeping bentgrass seed (PLS) ha^{-1}on 30 May, 2003 using a shaker bottle. Each main plot was then split into two sub-plots measuring 1.6 x 1.6 m, with each subplot randomly assigned traffic or no traffic. Buffers, 30.5 cm wide, surrounded each main plot and were planted with Penn G-2 creeping bentgrass. Buffers between each main plot, 0.3 m wide, and a large buffer around the entire area was seeded with Penn G-2. Germination blankets (A.M. Leonard, Piqua, OH) were placed over the seeded area and were removed on 9 June.

Before seeding, a soil analysis revealed that phosphorus and potassium were not limiting. Starter fertilizer (13N-11P-10K) was applied at a rate of 24 kg N ha^{-1} on the day of seeding. During the grow-in period, between 9 June and 23 September, 216 kg N ha^{-1} were applied to the turf on nine occasions at 24 kg N ha^{-1} in evenly spaced increments.

Once established, N was sprayed on the putting green in increments of 10 kg N ha^{-1} for a total of 90 kg N ha^{-1} during the growing season. One fertilization at a higher rate, 24 kg N ha^{-1}, was made in the spring of 2004 to promote annual bluegrass seedhead production, so the two species could be more easily distinguished for rating purposes. The fertility schedule and use of two different sources of nitrogen is outlined in Table 3.

The putting green was mowed five days per week with a Toro Greensmaster 1000 walk-mower (Minneapolis, MN) at a bench height of 3.2 mm (0.125 inches). Clippings were removed from the green. The putting green was lightly topdressed using a Toro Quickpass (Minneapolis, MN) with sand at intervals of approximately one week between 9 July and 23 September of 2003 to create a smooth surface so the desired mowing height could be met without scalping the turf. Sand topdressing was reinitiated in June of 2004, but was reduced in frequency to twice per month. The green was irrigated as needed to return 80% of evapotranspiration (ETp).

Traffic

The traffic data collected at Forest Akers Golf Course (Chapter 1) from 78 rounds of golf were extrapolated to 200 rounds of golf (Table 4) and were applied to 16 square plots with inner and outer rings whose surface areas were equal to the circles at Forest Akers Golf Course. The traffic was applied on the putting green at the HTRC as if a pin were being moved daily. Specific amounts of foot traffic, proportional to the data taken from the observational study (Chapter 1), were applied to outer and inner square rings which made up each trafficked plot on the putting green. Traffic was applied by two people weighing between 77 and 90 kg, each wearing Foot-Joy® DryJoy® golf

Table 3: Fertility schedule for a creeping bentgrass putting green.

Source of Nitrogen	2003									2004									
	17 June‡	25 June	3 July	10 July	24 July	30 July	12 Aug	9 Sep	23 Sep	29 April	11 May	20 May	7 June	15 June	1 July	19 July	10 Aug	30 Aug	21 Sep
24 kg N ha^{-1} 40-0-0 † Granular																			
10 kg N ha^{-1} Liquid Urea																			
24 kg N ha^{-1} Liquid Urea																			

† 25.5% urea and 14.5% WIN (water insoluble nitrogen)

‡ Date of fertilizer application- shaded box indicates source of nitrogen for that date.

Table 4: Traffic schedule for HTRC creeping bentgrass plots; footsteps estimated for 200 rounds of golf per day.

Day Traffic Executed	Pin Placement†	Footsteps		Time (seconds)
		Inner Circle	Outer Circle	
Saturday	1	0	0	-‡
Tuesday	2	18	26	-
Friday	3	13	26	-
Wednesday	4	33	49	-
Monday	5	56	113	83
Thursday	0	272	472	420

† Corresponds to one of six sectors on the putting green in Chapter 1 used to quantify traffic.

‡ Footsteps were few enough to count for each plot.

shoes equipped with Softspikes® Black Widow® spikes. On Mondays and Thursdays, the highest traffic days, an interval of time was used to quantify the number of footsteps applied (Table 4), so traffickers could measure applied traffic using a time limit per plot instead of counting our actual footsteps. This time limit was obtained by timing three foot traffic occasions and using the average of the three. On all other days, the footsteps were actually counted. Traffic began on 24 September 2003, when the turf had sufficiently grown in, and ended 2 weeks later. In 2004, traffic began on 21 April and ended in early October.

Plots were evaluated using visual quality ratings, annual bluegrass quantification by two different methods, and plant counts of each bentgrass cultivar. Visual ratings of quality were based on a 1-9 scale where 1=dead, 5=acceptable, and 9=excellent. Quality ratings included turf color, density, uprightness, and uniformity. Four subsamples per plot were collected in October, 2004 with a soil probe measuring 19 mm in diameter, and shoot counts were from these subsamples. Shoots were counted by using tweezers to remove shoots from each sample one by one. Annual bluegrass invasion was measured on a near-monthly basis by counting the centers of annual bluegrass in each plot. Annual bluegrass centers are small populations that colonize within the creeping bentgrass turf over time. These ratings were later supplemented with another method using line-intersecting grid counts. The grid was constructed to fit the 1.6 x 1.6 m sub-plots and consisted of 441 intersections, each measuring 76 x 76 mm. Annual bluegrass invasion was measured by counting the number of grid intersections which touched any part of an annual bluegrass plant. All annual bluegrass invasion data were collected from each trafficked plot, the inner and outer rings, as a whole.

The experimental design was a split plot randomized block design with four replications. Creeping bentgrass and traffic rate were treatment factors. Analysis of variance was used to determine significant effects ($P<0.05$) and, when significant, treatment differences were analyzed using the Proc Mixed procedure of SAS (SAS Institute, 2002). The 23 September, 2003 annual bluegrass invasion rating date was analyzed as a single factor, creeping bentgrass cultivar, design because traffic had not yet begun. When appropriate, means were separated using Fischer's LSD procedure at the 0.05 level of probability.

RESULTS AND DISCUSSION

Annual Bluegrass Invasion

The creeping bentgrass cultivars grew for four months before fall foot traffic began. After four months there was an average of 73 annual bluegrass centers, measuring approximately 3.3 cm^2, per plot. In 2004, annual bluegrass centers, averaged over all treatments, steadily increased from April to August and made a marked jump from 137 to 349 centers per plot between August and October.

There were only significant differences between traffic treatments on annual bluegrass invasion on the last three rating dates (Table 5). Analysis of the line-intersecting grid counts, performed in correspondence with the last three annual bluegrass center counts, revealed that trafficked plots had the greatest annual bluegrass invasion (Table 6), which supported the findings on the last three annual bluegrass center counts (Table 7). Intuitively, as traffic accumulates on a putting green, the health of the turfgrass decreases making it less able to compete with any weed. Foot traffic increases the ability of annual bluegrass seed to germinate within a turf stand by creating openings. There was a definite threshold at which the accumulated amount of foot traffic became a significant effect of annual bluegrass invasion into the creeping bentgrass putting green. Traffic did not become a significant effect of annual bluegrass invasion until 11 weeks of foot traffic accumulated at 1076 foot steps $week^{-1}$ $plot^{-1}$.

Results from annual bluegrass invasion ratings revealed that creeping bentgrass cultivar had a significant main effect on five of seven rating dates (Table 5). Providence had the highest relative annual bluegrass invasion on every rating date except for one, 7 April, 2004 (Table 8). Conversely, Penncross and Bengal each had the lowest annual

Table 5. Analysis of variance for annual bluegrass center counts in a creeping bentgrass green.

Source of Variation	df	2003	2004					
		23 Sep	7 April	22 April	13 May	6 July	4 Aug	28 Sep
Blocks	3							
Cultivar	3	*	*	*	*	NS	NS	*
Traffic	1	NS	NS	NS	NS	*	*	*
Cult*Traffic	3	NS	NS	NS	NS	NS	NS	NS
Error	12							

* and NS indicate significant and not significant at the $\alpha = 0.05$ probability level, respectively.

Table 6. Annual bluegrass invasion of a creeping bentgrass putting green as affected by the main effect of traffic using the line-intersecting grid rating method.

Traffic Treatment	2004		
	8 June	10 Aug	28 Sep
	———annual bluegrass plants†———		
Traffic	76	111	132
No Traffic	42	74	84
LSD (p=0.05)	12	17	41

† Number of annual bluegrass plants found from 441 line-intersections.

Table 7. Annual bluegrass invasion of a creeping bentgrass putting green as affected by the main effect of traffic.

Traffic Treatment	2003	2004					
	23 Sep	7 April	22 April	13 May	6 July	4 Aug	28 Sep
	annual bluegrass centers per plot						
Traffic	74	60	110	120	160	174	452
No Traffic	72	52	93	114	96	99	245
LSD (p=0.05)	NS	NS	NS	NS	21	29	80

NS indicates not significantly different at the p=0.05 probability level.

Table 8. Annual bluegrass invasion of a putting green as affected by the main effect of creeping bentgrass cultivar.

Cultivar	2003	2004					
	23 Sep	7 April	22 April	13 May	6 July	4 Aug	28 Sep
	annual bluegrass centers per plot						
Penncross	63a[†]	68c	94ab	97a	141	115	286a
Providence	93b	57b	123c	144b	144	134	362ab
Penn G-2	63a	56b	109bc	143b	117	121	270a
Bengal	74a	44a	81a	84a	109	177	476b
LSD ($p=0.05$)	17	9	22	36	NS	NS	119

† Means in a column followed by the same letter are not significantly different according to Fischer's protected LSD ($p=0.05$).
NS indicates not significantly different at the $p=0.05$ probability level.

bluegrass invasion on every rating date but one, Penncross on 7 April and Bengal on 28 September, 2004. Significantly fewer annual bluegrass centers were counted in Penn G-2 plots than Providence plots on the first rating date in 2003; thereafter, there were no differences in annual bluegrass invasion ratings between Penn G-2 and Providence (Table 8). Analysis of the line-intersecting grid counts of annual bluegrass, performed in correspondence with the last three annual bluegrass center counts, revealed no significant differences between creeping bentgrass cultivars on any of the last three dates (data not presented).

The putting green was established over an area previously maintained as an annual bluegrass fairway for many years and, therefore, is certain to have an atypically large annual bluegrass seed-bank. The resulting weed pressure from the large seed-bank could have diminished any cultivar main effects observed early in the study and helps to explain the lack of differences later. If this area was not previously maintained exclusively for annual bluegrass survival and dominance, the annual bluegrass seed-bank would have needed time to develop. Initially, annual bluegrass invasion may have been more subtle and differences among creeping bentgrass cultivars may have been more apparent and/or prolonged because weed pressure would have been initially very low and steadily increased as the annual bluegrass seed-bank increased.

There were no interactions between creeping bentgrass cultivars and traffic rates on any rating date. Although the accumulation of foot traffic did increase the annual bluegrass invasion averaged over all creeping bentgrass cultivars, this effect was not enhanced on any one creeping bentgrass cultivar on any rating date.

Shoot Density

Creeping bentgrass shoot densities ranged from 977 to 1379 shoots dm^{-2}. The main effect of traffic on creeping bentgrass shoot density was not significant. The main effect of creeping bentgrass cultivar on creeping bentgrass shoot density was significant (Table 9). Bengal and Penn G-2 had the highest shoot densities, while Providence and Penncross had the lowest shoot densities (Table 9). These shoot density rankings were consistent with previous research, while actual shoot density numbers were lower than many researchers have reported (Beard et al., 2001; Croce et al., 1999; Jordan et al., 2003; Sifers et al., 2001). The shoot densities, though, were very comparable to shoot densities observed by Sweeney et al. (2001) and much higher than those found by Geurtal (2004).

It was expected that the creeping bentgrass cultivar with the highest plant density would have accumulated the least annual bluegrass. However, in this case, Bengal, which had the highest shoot density in October of 2004 (Table 9), also had the highest annual bluegrass invasion on 28 September, 2004 (Table 8). Penncross, the oldest of the four cultivars and notorious for its prostrate growth habit had the lowest plant density in October of 2004 (Table 9), but was in the least annual bluegrass invasion category with Penn G-2 on 28 September, 2004 (Table 8).

Beard et al. (2001) found that Penncross and Pennlinks ranked lowest among 13 cultivars in aggressiveness against annual bluegrass invasion, while high-shoot density creeping bentgrass cultivars discouraged annual bluegrass invasion. Turgeon (2002) also found that Penn A-4, a high-shoot density creeping bentgrass cultivar, was more competitive against annual bluegrass than Penncross and Pennlinks.

Table 9. Shoot counts of a putting green turf as affected by the main effect of creeping bentgrass cultivar.

Cultivar	2004
	October
	shoots/dm²
Penncross	977c†
Providence	1119bc
Penn G-2	1316ab
Bengal	1379a
LSD (p=0.05)	235

† Means in a column followed by the same letter are not significantly different according toFischer's protected LSD (p=0.05).

However, Beard et al. (2001) and Turgeon (2002) were only evaluating creeping bentgrass competitive ability with the vegetative aspect or lateral growth of annual bluegrass. They observed the growth of an annual bluegrass plug within a creeping bentgrass stand, whereas our research evaluated creeping bentgrass competition with annual bluegrass lateral growth and seed germination.

Although Penn G-2 and Bengal produced denser turf stands than Penncross (Table 9), the data from this research revealed that Penncross was able to compete with annual bluegrass as well or better than Penn G-2 and Bengal on every rating date, except 7 April, 2004, which is counterintuitive to the findings of Beard et al. (2001) and Turgeon (2002).

Turfgrass Quality

There were significant differences in quality among creeping bentgrass cultivars on each of the four rating dates (Table 10). Penncross had the lowest quality on every rating date, while Bengal had the highest quality on every rating date. Penn G-2 quality was only significantly lower than Bengal on 22 April, 2004 (Table 11). Traffic negatively affected turfgrass quality on the last three rating dates (Table 12). High density creeping bentgrass cultivars, such as Penn G-2 have been reported to have higher turfgrass quality than low density cultivars (Croce et al., 1999; Sifers et al., 2001).

Table 10. Analysis of variance for turfgrass quality in a creeping bentgrass green.

Source of Variation	df	2004			
		7 April	22 April	13 May	6 July
Blocks	3				
Cultivar	3	*	*	*	*
Traffic	1	NS	*	*	*
Cult*Traffic	3	NS	NS	NS	NS
Error	12				

* and NS indicate significant and not significant at the $\alpha = 0.05$ probability level, respectively.

Table 11. Quality of a putting green as affected by the main effect of creeping bentgrass cultivar.

Cultivar	2004			
	7 April	22 April	13 May	6 July
	Quality†			
Penncross	4.6 b‡	4.6 b	4.9 c	3.9 c
Providence	5.6 a	5.0 b	5.4 bc	4.6 b
Penn G-2	5.6 a	5.0 b	5.9 ab	6.8 a
Bengal	5.9 a	6.1 a	6.5 a	6.8 a
LSD (p=0.05)	0.7	0.5	0.8	0.6

† Quality: 1=poor, 5=acceptable, and 9=excellent.

‡ Means in a column followed by the same letter are not significantly different according to Fischer's protected LSD (p=0.05).

Table 12. Quality of a creeping bentgrass putting green as affected by the main effect of traffic.

Traffic Treatment	2004			
	7 April	22 April	13 May	6 July
	Quality†			
Traffic	5.5	4.8	5.1	5.1
No Traffic	5.4	5.6	6.2	5.9
LSD (p=0.05)	NS	0.5	0.4	0.4

† Quality: 1=poor, 5=acceptable, and 9=excellent.
NS indicates not significantly different at the p=0.05 probability level.

CONCLUSIONS

Competition between turfgrass species can occur in tillers and/or roots (Danneberger, 1993). Generally, though, the competitive outcome between two turf species is decided by tillering capacity (Grimes and Hunt, 1975; Lush, 1988). Tillering capacities of turfs differentially fluctuate between species and cultivars within species due to temperature optimums for each (Danneberger, 1993). Furthermore, growth limits imposed by space, nutrients, and energy availability (Danneberger, 1993) differ between creeping bentgrass cultivars with differing characteristics, such as shoot density, root biomass, and leaf width. Factors differing among creeping bentgrass cultivars, such as shoot density and leaf width also affect annual bluegrass seed germination.

Among twelve creeping bentgrass cultivars, Beard and Sifers (1997) reported Penncross, Penn G-2, and Penn G-6 possessed the highest rooting biomass levels. They also found that Penncross and Penn G-2 had the best summer-stressed root biomass levels. Among these twelve cultivars, Beard and Sifers (1997) reported that all cultivars exhibited a decline in shoot density after the summer heat stress period, except for Penncross, Pennlinks, and Seaside II.

In this research, Penncross and Penn G-2 had the lowest annual bluegrass invasion on the last rating date (Table 4), which followed the hottest stretch of summer in 2004, while annual bluegrass centers in Bengal and Providence dramatically increased. These results support the findings of Beard and Sifers (1997) that Penncross and Penn G-2 performed well relative to other cultivars through summer-stress periods.

Although parts of this research may parallel other research findings, it is difficult to be certain of the reasons for these four cultivars fluctuating competitive abilities with annual bluegrass because there are so many possible factors. Penncross competed with annual bluegrass equally as well as Penn G-2 and Bengal on most rating dates, although it has a much lower shoot density than both. In this study, shoot density was not the governing creeping bentgrass cultivar characteristic for annual bluegrass invasion. Many factors affecting tillering capacity govern a creeping bentgrass's ability to effectively compete with annual bluegrass.

The main effect of traffic on creeping bentgrass shoot density was not significant. Although traffic disfavors the health of any turfgrass, it is also possible that it may do so without decreasing the turf density, which occurred in this study. However, a trafficked, and, thus, less healthy turfgrass may not compete with annual bluegrass as well as the same turf without applied traffic, which occurred in this study, although both may have the same number of shoots unit area^{-1}.

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