Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology
http://pip.sagepub.com/

Improving surface stability on natural turfgrass athletic fields

T J Serensits, A S McNitt and D M Petrunak

Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 2011 225: 85
DOI: 10.1177/1754337110396013

Improving surface stability on natural turfgrass athletic fields

T J Serensits*, **A S McNitt,** and **D M Petrunak**
Center for Sports Surface Research, The Pennsylvania State University, University Park, Pennsylvania, USA

The manuscript was received on 30 August 2010 and was accepted after revision for publication on 16 November 2010.

DOI: 10.1177/1754337110396013

Abstract: Regardless of the intensity of use, athletic fields are expected to provide a safe stable playing surface. As field use increases, wear caused by foot traffic can result in a loss of both turfgrass coverage and surface stability, increasing the risk of athlete injury. As surface stability is reduced, susceptibility to divoting is increased. The effect of synthetic soil reinforcements on the divot resistance of perennial ryegrass (*Lolium perenne* L.) under various simulated traffic levels was investigated. Soil-reinforcing materials improved divot resistance most under high traffic. Because the plant growth regulator trinexapac-ethyl (TE) has been shown to increase tiller density and rooting, its effect on divot resistance was evaluated on turfgrass grown on a sand root zone. TE (0.17 kg active ingredient/ha) was applied to Kentucky bluegrass (*Poa pratensis* L.) at 28 day intervals from either May to July or May to October. Plots were subjected to various levels of simulated traffic in the fall. Compared with the control, the application of TE from May to July resulted in the highest divot resistance. Various methods such as the inclusion of soil reinforcements and plant growth regulator applications can be used to decrease susceptibility to divoting.

Keywords: divot, surface stability, soil reinforcement, plant growth regulator

1 INTRODUCTION

Most natural turf athletic fields constructed using native soils high in silt and clay typically exhibit low infiltration rates, poor soil aeration, and excessive moisture holding during wet periods. When economically feasible, athletic field root zones are constructed using a high-sand (greater than 90 per cent) mixture to improve conditions for both plant growth and playability. However, a consequence of using a high-sand root zone is a lack of cohesion between sand particles, resulting in poor surface stability and susceptibility to divoting, especially as turfgrass plants are worn away during intense use [**1**]. The surface stability of an athletic field plays a critical role in the overall playability and safety of the surface.

Divoting may be thought of as the complete shearing, or removal, of the turf–shoot system from the remainder of the root zone. Root zones with low surface stability typically experience a high amount of divoting during an athletic event. Thus, a good indicator of surface stability is divot resistance. Few studies have evaluated divot resistance because of the difficulty in accurately replicating how athletes create divots. Adams [**2**] and Beard and Sifers [**3**] each used a weighted pendulum with a golf club head attached to one end to evaluate the divot resistance on athletic fields. Results from unpublished research comparing five divot-resistance-measuring devices indicated that a weighted-pendulum instrument provided the most reliable and consistent data. While a number of factors such as shoe type and player weight influence divoting, the amount of above- and below-ground biomass is the primary factor

**Corresponding author: Center for Sports Surface Research, Department of Crop and Soil Sciences, The Pennsylvania State University, 116 ASI Building, University Park, PA 16802, USA. email: serensits@psu.edu*

affecting resistance to divoting on high-sand root zones [**4**]. As a result, heavily trafficked fields with high-sand root zones can be susceptible to considerable divoting as turf coverage and the associated root system are reduced.

Synthetic reinforcements have been installed into the root zones of natural turfgrass to serve as an artificial root system and to increase divot resistance after turfgrass roots are reduced owing to traffic [**5**]. The majority of reinforcing materials that have been studied in turfgrass systems consist of polypropylene fibres which are amended into the root zone [**6**]. Disadvantages of synthetic reinforcements include increased surface hardness under dry conditions, increasing the risk of injury [**7**], and decreased water content, increasing the chance of turf injury [**8**]. Some reported benefits include increased linear traction [**7**], increased water infiltration rate [**8**], and increased shear resistance [**9**], an indication of divot resistance.

Synthetic reinforcements have also been reported to reduce divot size and to improve divot recovery [**3**, **10**]. Although differences between reinforced and non-reinforced treatments were observed in these studies, the magnitude of the differences was small (several millimetres). A reason why only small differences were detected may be that the plots were not exposed to traffic. As a result, the presence of a strong root system may have masked the effects of the reinforcements. The presence of roots has been shown to increase soil shear resistance by up to 300 per cent [**11**].

While synthetic reinforcements serve as an artificial root system because the turfgrass plant density is reduced owing to foot traffic, the application of a plant growth regulator may enhance the existing root system and growth of the natural turfgrass, making it more divot resistant. Trinexapac-ethyl (TE) is a commonly used plant growth regulator that reduces vertical shoot growth by limiting the production of gibberellic acid, the plant hormone responsible for cell elongation. Most commonly used for its reduction in shoot growth and, in turn, mowing frequency, there is also evidence that TE increases tiller density [**12**, **13**] and rooting [**14**, **15**]. Just as the presence of roots has been shown to increase shear resistance [**11**], increases in tiller density have been positively correlated with shear resistance [**16**].

Ervin and Koski [**17**] evaluated the potential for TE to be used on athletic fields. TE (0.27 kg/ha) was applied before and during simulated traffic. Based on the results of the study, they suggested caution when applying TE to athletic fields because of a dramatic decrease in clipping yield and subsequent inability to recover from damage. However, applying TE prior to simulated traffic and stopping applications as traffic commences may have a more positive effect. Ceasing applications at the onset of traffic may enable the field manager to take advantage of the post-suppression growth surge commonly observed as turfgrass is no longer under growth suppression. During the post-suppression growth surge, growth rates can be up to 160 per cent greater than untreated turf and the increased growth may improve early season recovery from damage [**18**].

The objectives of this research were to evaluate the effects of, first, synthetic reinforcing materials and, second, multiple-application regimes of the plant growth regulator TE on the divot resistance of natural turfgrass athletic fields.

2 METHODS

2.1 Plot construction

For the synthetic reinforcement study, field plots were established at the Joseph Valentine Turfgrass Research Center, University Park, Pennsylvania, USA. The plot area consisted of an under-drained gravel layer, approximately 150 mm deep, overlaid by a 65 mm intermediate layer. A 100 mm layer of sand and sphagnum root-zone mix was installed over the intermediate layer. Plots were seeded with SR 4200 perennial ryegrass (*Lolium perenne* L.) at a rate of 200 kg/ha. The plot size was 3.05 m by 3.05 m. Five synthetic reinforcing materials were used at various rates (Table 1).

For the plant growth regulator study, field plots were established at the Joseph Valentine Turfgrass Research Center, University Park, Pennsylvania, USA. The plot area consisted of an under-drained gravel layer, approximately 150 mm deep, overlaid by a 65 mm intermediate layer. A 254 mm layer of 80 vol % sand and 20 vol % peat was placed over the intermediate layer. A grid consisting of 27 plots, each measuring 3.05 m by 4.57 m, was laid over the level root-zone mix arranged in three rows of nine plots each. Each plot in each row was seeded with a different Kentucky bluegrass (*Poa pratensis* L.) cultivar and organized in a randomized complete block. The seeding rate was 97 kg/ha. The cultivars were Baron, Rugby II, Princeton 105, Touchdown, Limousine, Midnight, Langara, and two experimental cultivars (designated Experimental A and Experimental B). The subplots for the control and TE treatments measured 1.02 m by 0.91 m and the cultivation treatment subplots were 1.02 m by 1.83 m to accommodate the size of the aerification

Table 1 Treatments in the synthetic reinforcement study

Reinforcing material	Rates (g/kg)	Description
DuPont shredded carpet (DuPont Nylon, Wilmington, Delaware, USA)	5, 10, 20, and 30	The average length was 135 mm and the average width was 2.4 mm. When incorporated into the soil, DuPont shredded carpet is randomly oriented
Netlon discrete mesh elements (Netlon Ltd, Blackburn, UK)	3 and 5	The mesh is manufactured from extruded polypropylene and has a mass per unit area of 52 g/m^2. The filaments are arranged in a grid, creating rectangular openings that are 6.7 mm by 7.1 mm. Each element is 100 mm by 50 mm
Nike Reuse-A-Shoe materials (Nike, Beaverton, Oregon, USA)	30	Nike Reuse-A-Shoe materials are shredded remains of used athletic shoes. Nike supplied two materials for this study: Nike Lights and Nike Heavies. The Nike Lights contained 740 g/kg uppers, 230 g/kg midsole, and 30 g/kg outsole. The Nike Heavies contained 150 g/kg uppers, 510 g/kg midsole, and 340 g/kg outsole
Turfgrids (Synthetic Industries, Inc., Chattanooga, Tennessee, USA)	3 and 5	Turfgrids is a commercially available polypropylene fibre-reinforcing material. Individual fibres are 38 mm long and 5 mm wide. When mixed with soil, each fibre expands and the net-like configuration of fine fibres is randomly oriented throughout the root zone
Sportgrass (Sportgrass, Inc., McLean, Virginia, USA)	—	Sportgrass is a commercially available product consisting of polypropylene woven backing with 24 yarn strands per 25.4 mm in the lineal direction and 11 yarn strands per 25.4 mm in width. The woven backing is tufted with fibrillated polypropylene tufts with a pile height of 32 mm

Fig. 1 The Brinkman traffic simulator that was used to simulate athletic field use

unit. There were 324 subplots in total. Each cultivar plot received all applied treatments and all traffic levels.

Treatments included two TE application regimes and a cultivation treatment. TE (0.17 kg active ingredient/ha) was applied every 28 days from either May to July or May to October using a carbon dioxide backpack sprayer at a pressure of 345 kPa and a spray volume of 383 l/ha. A single-nozzle boom equipped with a flat fan nozzle 11004E was used. The cultivation treatment consisted of a combination of vertical mowing and core cultivation. Vertical mowing was performed using a Ryan Mataway (Cushman Inc., Lincoln, Nebraska, USA) walk-behind vertical mowing unit equipped with vertical blades spaced 2.5 cm apart. The unit was set to penetrate approximately 1.3 cm below the soil surface. Core cultivation immediately followed vertical mowing and was accomplished using a Toro Greens Aerator (Toro Company, Bloomington, Minnesota, USA) equipped with hollow tines of diameter 1.3 cm and spacing 6.4 cm. Cores were manually removed. The cultivation treatment was performed during the first week of May each year.

2.2 Trafficking conditions

In both studies, traffic was applied using a Brinkman traffic simulator [**19**] (Fig. 1). For the synthetic reinforcement study, levels of traffic were no traffic, medium traffic (three passes, three times per week), and high traffic (five passes, three times per week). Simulated traffic began at the beginning of June and ended in mid-October. For the plant growth regulator study, traffic levels were no traffic, medium traffic (two passes, three times per week), and high traffic (four passes, three times per week). Simulated traffic began at the end of July and ended at the end of October. Typically, traffic was applied regardless of the weather conditions or the soil water content. Occasionally, because of heavy precipitation or schedule conflicts, traffic was not applied on the scheduled day. In these cases, traffic was applied the following day.

2.3 Data collection

Following the final traffic application in both studies, divots were created using the head of a golf club pitching wedge attached to the end of a weighted V-shaped pendulum with a 30° angle between the shaft holding the weight and the shaft with the golf club head attachment (Fig. 2). The pendulum was weighted with a 76 kgf weight consisting of a steel cylinder

Fig. 2 A weighted pendulum with a golf club head attached to one end that was used to create divots

filled with lead. The pitching wedge and pendulum were fastened to the three-point hitch of a tractor. The height of the head relative to the treatment surface was controlled with adjustable metal pads. The pads can be set at different heights and, when the three-point hitch is lowered, the pad rests on the surface. To make a divot, the pendulum was released from a horizontal position. After the head of the pitching wedge cut through the soil surface, the maximum length of each divot was measured. Three divots were created and measured on each subplot. The length, width, and depth of each divot were measured. Because the width and depth were largely controlled by the device, the divot length was used to determine the divot resistance, with smaller divots indicating a higher divot resistance. There is currently no standard method for measuring the divot resistance. Although this method does not attempt to replicate all variables that affect the divot resistance (i.e. shoe type), the length of divots created using this method are largely affected by the amounts of the above-ground biomass and below-ground biomass, which have been shown to be the primary factors affecting the divot resistance [**4**]. Typical divots are shown in Fig. 3.

Fig. 3 Divots created by the weighted-pendulum device

In the plant growth regulator study, tiller density measurements were taken once per year. Four cultivars of Kentucky bluegrass, namely Limousine, Rugby II, P105, and Midnight, were selected for evaluation based on the cultivars' various degrees of divot resistance. Two cores (25 mm diameter and 67 mm deep) per plot were randomly extracted on 27 November 2006 and 29 November 2007. The cores were refrigerated at 5 °C until analysed. The tiller numbers were determined for each plug by cutting the plant shoots to soil level and counting each tiller. The average tiller numbers for the two subsample cores were used to represent the tiller density of the subplot. The same cores that were used for tiller density measurement were also utilized for evaluation of the below-ground biomass. After determining the number of tillers on each core sample, the thatch layers were removed and the cores were cut to a 25.4 mm depth. Cores were placed into a sieve with openings of diameter 0.15 mm and submersed into a tub filled with water in order to remove soil from the below-ground biomass. After most of the soil was separated from the below-ground biomass, the samples were oven dried at 60 °C for 24 h. The oven-dried samples were weighed and then ashed in a furnace at 440 °C for 16 h [**20**]. The difference between the masses before and after loss on ignition was used to represent the amount of below-ground biomass.

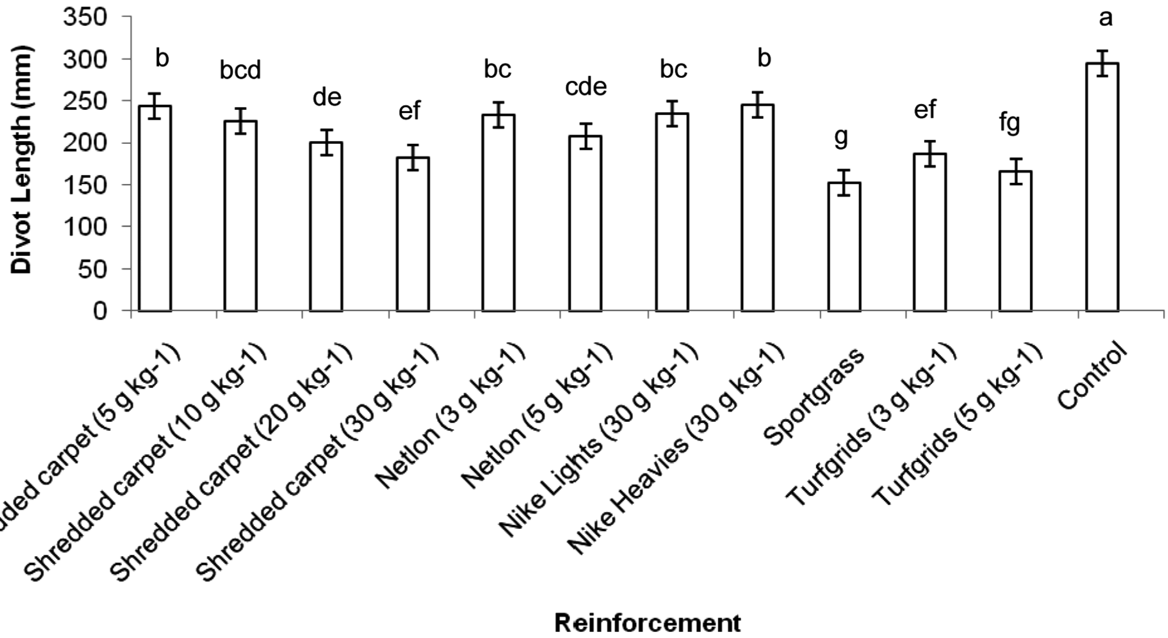

Fig. 4 Mean divot lengths for the synthetic reinforcement main effects ($p < 0.01$). The vertical lines denote Fisher's LSD at the 0.05 probability level; treatments with the same letters are not statistically different

2.4 Experimental design

The experimental design of the synthetic reinforcement study was a split block (blocks split by three levels of traffic) with 12 treatments and three blocks. The mean of three divot length measurements per subplot was used to represent the divot resistance of each subplot. The experimental design of the plant growth regulator study was a strip–split plot design with three replications. Simulated traffic was the strip and the applied treatments acted as the split. The mean of two divot length measurements per plot was used to represent the divot resistance of each subplot. For each study, the means were analysed using analysis of variance and least-significant-difference (LSD) tests at the 0.05 level. An LSD was not calculated when the F ratio was not significant at the 0.05 level.

3 RESULTS AND DISCUSSION

3.1 Synthetic reinforcement study

Traffic level affected divot length as the no-traffic treatment (153 mm) had shorter divots than the medium-traffic level (247 mm) and high-traffic level (241 mm). The medium- and high-traffic levels were not statistically different from one another ($p > 0.05$). These data indicate that, as more traffic is imposed on a perennial ryegrass turf growing in a high-sand root zone, the larger the divots become. Generally, a lower turf density resulted in a lower soil strength as evidenced by a greater divot size, even when reinforcing materials were present.

All reinforcing materials resulted in a smaller mean divot length than the control ($p < 0.01$) (Fig. 4). Sportgrass had smaller divots than any other treatment. Sportgrass reduced divot length compared with the control by approximately 48 per cent. Nike Lights, Nike Heavies, and Netlon at the low rate (3 g/kg) had the smallest effect on divot length.

The data for the synthetic reinforcement by traffic level interaction ($p < 0.01$) are shown in Fig. 5 (high traffic only). Under the no-traffic treatment, only Turfgrids at the high rate (5 g/kg) had shorter divots than the control (data not shown). Under medium-traffic levels, all synthetic reinforcements reduced divot length compared with the control with the exception of Nike Heavies (data not shown). All synthetic reinforcements had smaller divots than the control under high-traffic levels. Overall, there were greater differences among treatments as the traffic level increased and the turfgrass density decreased, indicating that, at 100 per cent turf cover, the perennial ryegrass root system most probably masked the divot resistance effect of the reinforcements. Overall, the reinforcing materials resulted in a smaller divot size than the control only after turfgrass cover was significantly reduced. The

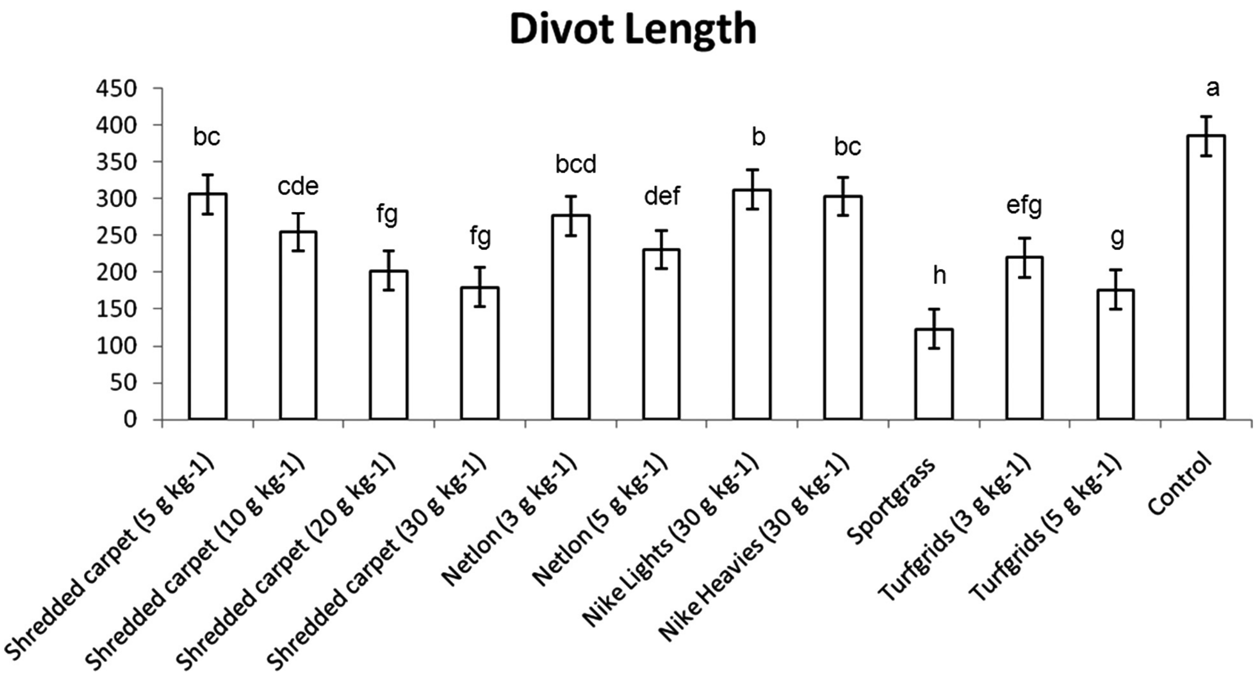

Fig. 5 Mean divot lengths for the treatment by traffic interaction ($p < 0.01$, high traffic only shown). The vertical lines denote Fisher's LSD at the 0.05 probability level; treatments with the same letters are not statistically different

rate effects of DuPont Shredded Carpet, Netlon, and Turfgrids are evident in the interaction data, as an increasing rate of the reinforcing materials resulted in smaller divots under the high-traffic level. The reduction in divot size is in general agreement with the trends reported by Beard and Sifers [**3**, **10**], although the range of the divot lengths in this experiment is greater, probably because of the simulated foot traffic.

3.2 Plant growth regulator study

In the same way as in the synthetic reinforcement study, traffic level affected the divot length (data not shown). As the traffic level increased, the divot length increased. Each traffic level was statistically different from the others ($p < 0.01$). The no-traffic treatment (270 mm) had shorter divots than the medium-traffic treatment (324 mm) and the high-traffic level (354 mm). As with the perennial ryegrass in the reinforcement study, as more traffic was imposed on the Kentucky bluegrass in this study, the divot length increased.

A significant study year effect for the treatment main effect was detected; data from each year are presented separately (Table 2). Overall, the application of TE from May to July was the most consistent and effective treatment for reducing the divot length in both years of the study. This treatment reduced the divot size by 56 mm in 2006 and by 27 mm in 2007. TE applied from May to October was effective at reducing divot length in 2006 but did not reduce divot size in 2007. Conversely, the cultivation treatment (core aerification combined with vertical mowing) reduced divot length in 2007 but not in 2006.

The treatment by traffic level interaction was non-significant, indicating that treatments performed similarly, regardless of the traffic level. For example, the application of TE from May to July provided the largest divot length reduction of all treatments at each traffic level compared with the control. These results indicate that an improved divot resistance can be achieved by applying TE from May to July regardless of the intensity of field use.

Measurements of tiller density show that TE applications significantly increased tiller density compared with untreated turf (Table 3). TE applied from May to October produced a 14 per cent increase in tiller density while TE applied from May to July increased tiller density by 9 per cent. The difference between tiller densities of the two TE treatments is most probably the result of the three additional TE applications per year in the TE treatment from May to October. An increase in the tiller density may help to explain why TE treatments generally reduced the divot length. These findings support the research of Shildrick and Peel [**16**],

Table 2 Mean divot length values for treatments in 2006 and 2007, where the mean separation is obtained by Fisher's LSD test at the 0.05 probability level, the numbers in parentheses indicate the standard errors of the mean, and treatments with the same letters within each column are not statistically different

	Divot length (mm)	
Treatment	2006	2007
Control	308 (±8) a	362 (±10) a
TE May–July	252 (±9) c	335 (±9) b
TE May–October	278 (±8) bc	370 (±9) a
Cultivation	282 (±10) ab	341 (±9) b
LSD (0.05)	27	18

Table 3 Mean tiller density and below-ground biomass values for treatments (both years combined), where the mean separation is obtained by Fisher's LSD test at the 0.05 probability level, the numbers in parentheses indicate the standard errors of the mean, and treatments with the same letters within each column are not statistically different

Treatment	Tiller density (tillers/m^2)	Below-ground biomass (g/m^2)
Control	1679 (±63) c	70.6 (±1.5) b
TE May–July	1828 (±71) b	76.3 (±2.1) a
TE May–October	1909 (±71) a	70.7 (±1.6) b
Cultivation	1677 (±65) c	70.0 (±1.5) b
LSD (0.05)	60	3.8

which described a positive correlation between tiller density and shear resistance.

Below-ground biomass was also affected by TE applications; however, only the TE treatment regime that included applications from May to July produced a significant effect (Table 3). Applying TE from May to July yielded an 8 per cent increase in below-ground biomass compared with the control. Other treatments and the control differed by less than 1 per cent. The combination of increases in below-ground biomass and tiller density offer insight as to why TE applied from May to July was the most effective treatment at reducing divot length. Other researchers have also reported positive benefits of an increased tiller density and below-ground biomass on surface stability [**11**, **16**, **21**]. Reasons as to why both TE treatments did not increase below-ground biomass are unclear. One possible explanation for this finding may be changes in the growth related to the post-suppression growth surge that may have occurred for the May-to-July treatment. The long-term effects of TE applications are not known. Samples for the below-ground biomass evaluation were extracted from the soil approximately 3 months after uninhibited growth resumed. More research is needed to determine the long-term physiological effects of returning to uninhibited growth following multiple TE applications.

4 CONCLUSIONS

Surface stability was improved using both synthetic reinforcements and plant growth regulators. The installation of synthetic reinforcements into the root zone of high-sand fields increased divot resistance. The greatest improvements were observed under the high-traffic level. It is presumed that the mature healthy root system of the turfgrass under the no-traffic level provided adequate stabilization to mask the effect of the reinforcing materials. As increased traffic decreased turfgrass density and presumably turfgrass rooting, divot size generally increased for all treatments. Under conditions where there is a significant reduction in turfgrass cover, a soil reinforcement rate effect was evident, in which increasing amounts of a particular reinforcement resulted in a decrease in divot size. The results of this study indicate that, on high-use athletic fields with high-sand root zones, the synthetic reinforcements used in this study can provide increased divot resistance.

The results of the plant growth regulator study indicate that resistance to divoting can be improved by applying TE from May to July on a field with a high-sand root zone that receives little to no play during the spring and summer. In addition to reducing divot size, TE applied from May to July also increased tiller density and below-ground biomass. TE applied from May to October increased tiller density; however, it only slightly improved divot resistance in only one of the two years and had no effect on below-ground biomass. Applications of TE while the field is in use have resulted in negative consequences on the turfgrass quality and traffic tolerance [**17**, **22**]. The results of this research suggest that, on a field with fall gameplay only, applying TE during the months prior to field use and then allowing the turf to resume uninhibited growth during the fall increases divot resistance. The results of this research provide a better understanding of the factors that affect surface stability and how those factors can be manipulated and enhanced to provide a more stable playing surface that maximizes safety and playability.

REFERENCES

1 **Henderson, J. J., Crum, J. R., Wolff, T. F.,** and **Rogers III, J. N.** Athletic field root zone mixes: what is the best mix for your field? In Proceedings of the 71st Annual Michigan Turfgrass Conference, East Lansing, Michigan, USA, January 2001, pp. 96–99 (Michigan Turfgrass Foundation, East Lansing, Michigan).

2 **Adams, W. A.** The effect of 'Fibermaster' fibres on the stability and other properties of sand rootzones. *Int. Turf. Soc. Res. J.*, 1997, **8**, 15–26.

3 **Beard, J. B.** and **Sifers, S. I.** Feasibility assessment of randomly oriented, interlocking mesh element matrices for turfed root zones. In *Natural and artificial playing fields: characteristics and safety features*, ASTM STP 1073 (Eds R. C. Schmidt, E. F. Hoerner, E. M. Milner, and C. A. Moorhouse), 1990, pp. 154–165 (ASTM International, Philadelphia, Pennsylvania).

4 **Rogers, J. M., Waddington, D. V.,** and **Harper, J. C.** Relationships between athletic field hardness and traction, vegetation, soil properties, and maintenance practices. Progress Report 393, College of Agriculture, Experimental Station, The Pennsylvania State University, University Park, Pennsylvania, USA, 1988, 15 pp.

5 **McNitt, A. S.** and **Landschoot, P. J.** The effects of soil reinforcing materials on the traction and divot resistance of a sand rootzone. *Int. Turf. Soc. Res. J.*, 2005, **10**, 1115–1123.

6 **Baker, S. W.** The reinforcement of turfgrass areas using plastic and other synthetic materials: a review. *Int. Turf. Soc. Res. J.*, 1997, **8**, 3–13.

7 **Baker, S. W.** and **Richards, C. W.** The effect of fibre reinforcement on the quality of sand rootzones used for winter game pitches. *J. Sports Turf Res. Inst.*, 1995, **71**, 107–117.

8 **Canaway, P. M.** and **Bell, M. J.** A field trial on isotropic stabilisation of sand rootzones for football using Netlon mesh elements. *J. Sports Turf Res. Inst.*, 1986, **70**, 100–109.

9 **Adams, W. A.** and **Gibbs, R. J.** *Natural turf for sports and amenity: science and practice*, 1994 (CB International, Wallingford, Oxfordshire).

10 **Beard, J. B.** and **Sifers, S. I.** A randomly-oriented, interlocking mish element matrices system for sports turf root zone construction. In Proceedings of the Sixth International Turfgrass Research Conference (Ed. H. Takatoh), Tokyo, Japan, 31 July–5 August 1989, pp. 253–257 (International Turfgrass Society and Japanese Society of Turfgrass Science, Tokyo).

11 **Van Wijk, A. L. M.** A soil technological study evaluating and maintaining adequate playing conditions of grass sports fields. Agricultural Research Report 903, Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands, 1980, 124 pp.

12 **Beasley, J. S., Branham, B. E.,** and **Ortiz-Ribbing, L. M.** Trinexapac-ethyl affects Kentucky bluegrass root architecture. *HortScience*, 2005, **40**, 1539–1542.

13 **Ervin, E. H.** and **Koski, A. J.** Growth responses of Lolium perenne L. to trinexapac-ethyl. *HortScience*, 1998, **33**, 1200–1202.

14 **McCullough, P. E., Liu, H., McCarty, L. B., Whitwell, T.,** and **Toler, J. E.** Nutrient allocation of 'tifeagle' bermudagrass as influenced by trinexapac-ethyl. *J. Plant Nutr.*, 2006, **29**, 273–283.

15 **Qian, Y. L.** and **Engelke, M. C.** Influence of trinexapac-ethyl on Diamond zoysiagrass in a shade environment. *Crop Sci.*, 1999, **39**, 202–208.

16 **Shildrick, J. P.** and **Peel, C. H.** Shoot numbers, biomass, and shear strength in smooth-stalked meadow-grass (Poa Pratensis). *J. Sports Turf Res. Inst.*, 1984, **60**, 66–72.

17 **Ervin, E. H.** and **Koski, A. J.** Kentucky bluegrass growth responses to trinexapac-ethyl, traffic, and nitrogen. *Crop Sci.*, 2001, **41**, 1871–1877.

18 **Lickfeldt, D. W., Gardner, D. S., Branham, B. E.,** and **Voigt, T. B.** Implications of repeated trinexapac-ethyl applications on Kentucky bluegrass. *Agron. J.*, 2001, **93**, 1164–1168.

19 **Cockerham, S. T.** and **Brinkman, D. J.** A simulator for cleated-shoe sports traffic on turfgrass research plots. *Calif. Turfgrass Cult.*, 1989, **39**, 9–10.

20 D2974-07a *Standard test methods for moisture, ash, and organic matter of peat and other organic soils*. In *Annual book of ASTM standards, vol. 04.08, Soil and rock (I)*, 2008 (ASTM International, West Conshohocken, Pennsylvania).

21 **Adams, W. A.** and **Jones, R. L.** The effect of particle size composition and root binding on the resistance to shear of sportsturf rootzones. *Rasen-Turf-Gazon*, 1979, **10**, 48–53.

22 **Marshall, C. S.** *The use of plant growth regulators to improve the traffic tolerance and repair of overseeded bermudagrass*. MS Thesis, Virginia Polytechnic Institute, Blacksburg, Virginia, USA, 2007.