# SEEDING PRACTICES FOR COOL-SEASON SOD GROWN ON PLASTIC PRODUCTION AND DOMED STADIUMS

By

Jackie Lyn Aguilar Guevara

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences – Doctor of Philosophy

2025

**ABSTRACT**

The demand for natural turfgrass in professional sports is increasing due to concerns over higher injury rates associated with artificial turf. However, domed stadiums often use artificial turf because these venues host events that do not require natural grass. To provide a temporary natural turfgrass playing surface, a shallow turfgrass profile – consisting of big roll sod grown on plastic (SOP) over geocellular drainage modules – has been developed. Kentucky bluegrass (*Poa pratensis* L.; KBG) is a commonly used cool-season grass in SOP production for sports fields, but it faces challenges due to its slow germination, which can lead to potential soil erosion during the early stages of establishment. Perennial ryegrass (*Lolium perenne* L.; PRG), known for its rapid germination, may stabilize the soil while KBG is still germinating. However, the optimal seeding ratios for combining these grasses in SOP production and domed stadiums remain unclear. Three studies were conducted: the first two studies focused on SOP production at the Hancock Turfgrass Research Center in 2023 and 2024, and the third study focused on controlled environments at the FIFA Indoor Pitch Simulator Facility in 2024. The first study aimed to evaluate the effects of different KBG:PRG seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16, 0:100) on cool-season SOP production. After four months, results indicated that even a small percentage of PRG significantly enhanced turfgrass cover, with the 84:16 KBG:PRG mix showing a 58% increase in tensile strength compared to the 100:0 ratio. This suggests that the 84:16 ratio is optimal for producing harvestable KBG-dominated sod in a short time frame. Unexpectedly, pure PRG (0:100) exhibited the highest turfgrass cover and tensile strength among treatments, highlighting the potential for PRG in SOP production. Hence, the second study aimed to determine the optimum PRG seeding rates (1.5, 3, 6, and 9 pure live seeds cm$^{-2}$) for SOP production. Results showed that the 1.5 PLS cm$^{-2}$ rate exhibited lower turfgrass coverage and shear strength at 4 weeks after seeding but higher tensile strength at 12 weeks compared to the higher seeding rates. The rates , 1.5 and 3 PLS $cm^{-2}$ , were identified as optimal for balancing turfgrass coverage and sod harvestability. Lastly, the third study aimed to investigate the effects of different KBG:PRG seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16, 0:100) during SOP production on turfgrass quality and performance under artificial lighting and trafficked conditions. Results indicated that traffic application significantly reduced turfgrass color and green cover, but KBG:PRG ratios showed similar performance in turfgrass color, percent green cover, maximum shear stress, and maximum displacement.

## ACKNOWLEDGEMENTS

I extend my heartfelt gratitude to my graduate committee for their support in ensuring my success. To my advisor, Dr. Trey Rogers, thank you for taking a chance on me as a young girl who unexpectedly showed up in your class and for helping me build the confidence to reach where I am today. To Dr. Kevin Frank, I am deeply grateful for your guidance and support throughout every step of my journey. To Dr. John Sorochan, thank you for your mentorship, friendship, and the inspiring stories you shared. To the late Dr. Joe Vargas, it was a tremendous honor to have you on my committee. To Dr. Brian Horgan, thank you for believing in me and giving me the opportunity to excel.

This journey would not have been possible without the support of the MSU Turf Team. To the Hancock Turfgrass Research Center staff, especially Jesse Sholl and Mike Rabe, thank you for your invaluable assistance throughout my research. To the MSU Turf faculty, Nancy Dykema, Dr. Thom Nikolai, and Dr. Emily Holm, I deeply appreciate your guidance and encouragement. To the past and current turf graduate students, thank you for supporting and uplifting one another throughout this journey. To my lab mates, Ryan Bearss and Evan Rogers, and my fellow crack staff member, Jake Kilby—thank you for standing by me through both the triumphs and challenges.

To the communities that became my home away from home: Migrant Student Services, The University Lutheran Church, PSM community and MSU Filipino community, thank you for making me feel welcome and giving me a place where I truly belong.

To my family and friends – too many to mention individually – please know how deeply grateful I am for each of you. To my husband, Arlo, your love has been the foundation of my journey. I could not have completed this program without you.

# TABLE OF CONTENTS

# CHAPTER 1: LITERATURE REVIEW

## History of sod production

*Conventional sod production*

Conventional sod production is the most common method of sod production, where sod is grown directly in the native soil. The land is cleared, plowed, harrowed, graded, and then seeded or sprigged. The sod is typically grown for one to two years to ensure that rhizomes, stolons, and/or tillers are fully knitted together (Daniel, 1962; Decker, 2001). During harvest, a sod cutter removes the sod from the soil by cutting through the roots, which can cause root damage. Thus, prompt care and immediate transplanting are essential for successful establishment (Decker, 2001). With the adoption of sand-based construction for sports fields and golf courses, challenges arise when sod grown on organic soils is transplanted onto a sand-based rootzone. The difference in soil textures causes water movement to slow as it transitions from coarser sand to finer material, leading to potential drainage issues (Gardner, 1988).

*Sod grown on plastic production*

An alternative approach to conventional sod production is sod grown on plastic. This method addresses some limitations of conventionally grown sod. Growing sod on an impervious layer, such as a plastic sheet, began in the 1960s at Ohio Wesleyan University and field trials at Buckeye Bluegrass Farms (Decker, 1975). In this method, primary roots make contact with the plastic, spread across its surface, and knit the growing medium into a cohesive sod (Decker, 1975, 1991).

Studies have shown that sod grown on plastic can be produced as early as five weeks which is quicker than conventionally grown sod (Decker, 1989). It also provides growers with full control over the root zone (Decker, 1975), as various growing mediums have been used and tested, including soilless media (Cisar & Snyder, 1992; Decker, 2001; Roberts et al., 2001; Sorochan & Rogers, 2001) and sand-based root zones designed for sand-based fields and golf greens to avoid layering issues. Sod grown on plastic can be easily harvested by rolling without damaging the roots, allowing it to establish quickly in a new location (Decker, 2001). However, challenges include the cost and availability of suitable growing medium and plastic sheeting, as well as the need for precise topdressing to ensure uniform thickness (Decker, 1989, 1991).

This method was found to be particularly useful for turfgrass species with a bunch-type growth habit – those that lack extensive rhizomes and stolons but have a strong primary rooting system – such as tall fescue (Decker, 1991). There is potential to use this sod production system to incorporate more bunch-type turfgrass species, such as perennial ryegrass (*Lolium perenne* L.; PRG).

*Big roll sod*

Sod was primarily harvested and laid as small rolls (Carrier, 1922) until the introduction of big roll sod in the 1960s. Beck Farm developed the first known big roll sod harvester to create a more economical method for laying and harvesting sod using machines instead of manual labor (Beck, 1991; Dover, 2000). By the 1980s, more companies began producing their own harvesters as the benefits of big roll sod became increasingly evident, especially with the labor shortage. Big roll sod offered significant advantages over small roll sod, including lower labor costs, reduced worker fatigue, and faster harvest and installation times (Beck, 1991; Dover, 1999; Dover, 2000). In the 1990s, big roll sod gained widespread use in stadiums and sports fields due to its fewer seams and ease of installation. These qualities allowed fields to be renovated in under 24 hours (Dover, 2000).

## Evolution of portable turfgrass systems

The demand for natural turfgrass playing surfaces in professional sports has been steadily increasing, driven by concerns over the higher injury rates associated with artificial turf (Gould et al., 2022). Organizations like the National Football League Players Association (Tretter, 2024) and the Fédération Internationale de Football Association (FIFA) have consistently advocated for the use of natural grass, with FIFA mandating that all World Cup matches be played on natural turfgrass surfaces (Fédération Internationale de Football Association, 2022).

However, many domed stadiums are multi-use venues that host a variety of events, not all of which require a natural grass surface. To maximize profitability, these venues often use artificial turf, as it allows for constant availability of the field for events. Converting these artificial turf fields into permanent natural grass surfaces is typically cost-prohibitive, with many of these fields eventually reverting to artificial turf (SportsTURF, 1997). This issue has driven the development of temporary natural grass systems, which can be easily installed and removed for specific events, thus providing a practical and cost-effective solution. These systems can be placed over concrete, asphalt, or similar flooring, offering a way to incorporate natural grass into venues that would otherwise use artificial turf (SportsTURF, 1997).

### *Palletized turf*

One of the early innovations in portable turfgrass systems is palletized turf, also known as modular turf. This system involves growing turfgrass on a root zone of 10 to 20 cm, within a specific-sized container (Li et al., 2015). The first use of palletized turf was during the 1993 United States Gold Cup (Germany vs. England), where steel hexagonal frames filled with a mix of sand, peat, and loam were used (Ripley & Indyk, 1993; Rogers et al., 1993, 1995). Over time, the design evolved into square trays filled with sand-based rootzones, including the ITM system, Hummer Grass Tile System  and StrathAyr  (Li et al., 2015). Palletized turf systems allowed for the rapid installation and removal of entire fields, often within a few days. However, this system remains labor- and time-intensive, requiring substantial space for field assembly before installation (Rogers et al., 1993, 1995).

*Retractable field*

Retractable fields were developed to address the labor-intensive process of manually moving a field in and out of a stadium. The first retractable field system was introduced in 1998 at GelreDome in Arnhem, Netherlands (Guinness World Records, 1998). In 2006, Cardinals Stadium, now known as State Farm Stadium in Arizona, became the first stadium in North America to adopt this technology (Newcomb, 2015; State Farm Stadium, 2024). More recently, in 2020, Allegiant Stadium in Nevada also implemented a retractable field system (Las Vegas Raiders, 2020).

This system requires a significant commitment from stadium operators, including dedicated storage space for the grass, regular maintenance, and system upkeep, all of which can be costly. State Farm Stadium and Allegiant Stadium use a system where the natural grass field slides out of the stadium to receive natural light and is maintained outdoors (Newcomb, 2015; Las Vegas Raiders, 2020). More sophisticated systems, such as the one at the Tottenham Hotspur Stadium (North London, UK), cost approximately £1 billion. It features a retractable field stored in an underground, garage-like area. The storage area is equipped with a controlled environment, including heating, cooling systems, and artificial lighting, to maintain the field in optimal playing condition (Ibbetson, 2019). Due to the significant investment required, retractable field systems are designed for more permanent facilities and long-term use.

*Shallow turfgrass profile*

Not all stadiums are inclined to invest in permanent retractable field systems, yet many still require natural turfgrass fields for certain events. Advancements in turfgrass technology, such as big roll sod and sod grown on plastic, have facilitated the development of shallow turfgrass profile systems. These systems are designed for quick and easy installation, allowing sod to be delivered directly from the sod farm and removed after events. Big roll sod grown on plastic, which can be laid directly over concrete, asphalt, or other flooring, has become a widely used solution for temporary fields in the United States (Odgaard, 2003). These systems can be installed and removed within a day but are intended for short-term use, typically lasting no more than a week.

However, there is a need for the extended use of shallow turfgrass profile systems inside stadiums. For instance, the temporary field for the FIFA World Cup 2026 may need to last six to eight weeks. To meet this need, turf systems now require irrigation, which also necessitates a drainage system. Plastic geocellular modules have emerged as an effective alternative to traditional gravel layers, offering a thin, portable, and easy-to-install option (Young et al., 2022). Research has demonstrated that these plastic geocellular modules perform comparably to standard gravel root zones used for golf course putting greens and sports fields (McInnes & Thomas, 2011; Rose-Harvey et al., 2012; Young et al., 2022). Guevara et al. (2024) found that perennial ryegrass sod grown on plastic on top of Permavoid 85s geocellular drainage (Permavoid, Amsterdam, NL) met FIFA requirements for surface hardness and ball rebound height, further validating the efficacy of the geocellular drainage module for high-performance sports fields. However, this type of shallow turfgrass profile system has yet to be tested with a cool-season sod grown on plastic in an indoor environment, simulating a domed stadium.

## Indoor turfgrass management

In addition to the process of installing a temporary natural turfgrass field within domed stadiums, effective turfgrass management is important in an indoor environment. Growing natural grass in indoor environments was first introduced in the 1990s in preparation for the 1994 World Cup (Beard et al., 1991; Rogers et al., 1993, 1995, 1997).

### *Artificial lighting*

Traditionally, high-pressure sodium (HPS) lighting systems have been used, as it provides both radiation and heat but are energy-intensive (Rogers et al., 1997). As an alternative, light-emitting diode (LED) technology was developed, offering several advantages over HPS. LEDs consume less energy, produce less heat, and have an adjustable light spectrum (Abélard & Galbrun, 2022). Research has shown that both HPS and LED systems can improve the performance of cool-season turfgrasses, such as perennial ryegrass (*Lolium perenne* L.; PRG), Kentucky bluegrass (*Poa pratensis* L.; KBG), and tall fescue (*Festuca arundinacea*), under shaded conditions by enhancing turfgrass quality, density, and wear tolerance. However, LEDs are preferred due to their lower energy consumption and customizable light spectrum, making them a more sustainable choice (Abélard & Galbrun, 2022).

### *Grasses*

Selecting the appropriate turfgrass species or mix is crucial for successfully growing grass inside a domed stadium. Warm-season and cool-season grasses have distinct physiological characteristics that influence their light requirements. Cool-season grasses require less light and are generally better suited to reduced light environments than warm season grasses (Cooper, 1970). For example, during the 1994 World Cup, the sod used for the field was seeded with cool-season grasses – 85% KBG and 15% PRG – on compost laid over plastic (Lehnert, 1993; Rogers et al., 1994).

## Kentucky bluegrass

KBG is the most commonly grown cool-season turfgrass species for sod production in the United States (Rieke & Beard, 1969). It has a high sod-forming ability because it produces underground stems, called rhizomes, that give rise to new shoots which knit the sod together (Rieke & Beard, 1969). KBG is widely used in sports fields due to its high traffic tolerance and good surface traction (McNitt et al., 1997; Minner & Valverde, 2005). However, it has the slowest germination rate among cool-season grasses, taking approximately 7 to 14 days to germinate (Braun et al., 2023; Folck et al., 2023).

## Perennial ryegrass

PRG is a widely used cool-season turfgrass species for sports fields due to its rapid germination rate and high wear tolerance (Braun et al., 2023; Głąb et al., 2024). However, its recuperative ability is limited because it has a bunch-type growth habit (Sherratt & Street, 2005). While perennial ryegrass can be grown conventionally, it cannot be harvested as big roll sod due to its growth habit. However, sod with a high percentage of fine fescues (*Festuca* spp.), which share a similar growth habit, has been found to achieve sod strength comparable to that of conventionally grown Kentucky bluegrass sod (Friell et al., 2017). This suggests that perennial ryegrass big roll sod could potentially be produced using the sod grown on plastic method. However, no research to date has specifically examined the use of this method for producing perennial ryegrass big roll sod.

## Kentucky bluegrass and perennial ryegrass mixes

The development of turf-type PRG has allowed the use of KBG/PRG seed mixtures (Niehaus, 1976), which are now commonly used in sports fields to improve genetic diversity and resilience to environmental stresses (Dunn et al., 2002). These mixtures have demonstrated superior turf cover and traffic tolerance compared to monocultures (Brede & Duich, 1984; Stier et al., 2008). However, the fast establishment and competitiveness of PRG can impede the establishment of KBG, potentially affecting the long-term composition of a KBG-dominated stand (Engel & Trout, 1980, Braun et al., 2023; Folck et al., 2023).

Studies have shown that when KBG and PRG are sown simultaneously, KBG often comprises only 3% to 30% of the tillers, despite accounting for 50% to 59% of the viable seeds in the mixture (Larsen et al., 2004). For instance, a 50:50 KBG-to-PRG mixture by weight resulted in a composition of 67% PRG and 27% KBG after four years (Hsiang et al., 1997). Gibeault et al. (1980) found that that an 85:15 KBG-to-PRG mixture by weight resulted in an approximate 50:50 plant ratio after three years. Proctor et al. (2015) observed that seeding ratios with a high proportion of KBG (80% to 90% KBG by weight) shifted to a stand dominated by more than 95% KBG within two years. Ratios lower in KBG followed a similar trend but required three years to reach a comparable composition.

## REFERENCES

Abélard, E., & Galbrun, C. (2022). The effects of artificial lighting on sports turf. *International Turfgrass Society Research Journal*, *14*(1), 1016–1021. https://doi.org/10.1002/its2.115

Beard, J., Milberger, A., & vanBavel, C. (1991). *Indoor Domed Stadia Natural Turf Feasibility Study: Final Report* (p. 43).

Beck, M. (1991). "Why we developed the big roll system." *Weeds Trees and Turf*, *10*(10), 26–28.

Braun, R. C., Courtney, L. E., & Patton, A. J. (2023). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, *63*(3), 1613–1627. https://doi.org/10.1002/csc2.20936

Brede, A., & Duich, J. (1984). Establishment characteristics of Kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. *Agronomy Journal*, *76*, 6. https://doi.org/10.2134/agronj1984.00021962007600060004x

Carrier, L. (1922). Sodding. *Bulletin of the Green Section of the U.S. Golf Association.*, *2*(12), 333–337.

Cisar, J., & Snyder, G. (1992). Sod Production on a Solid-waste Compost over Plastic. *HortScience*, *27*(3), 219–222. https://doi.org/10.21273/HORTSCI.27.3.219

Cooper, J. (1970). Potential production and energy conversion in temperate and tropical grasses. *Herbage Abstracts*, *49*, 1–15.

Daniel, W. (1962). Sod production. *Proceedings of 1962 Turf Conference Sponsored by the Midwest Regional Turf Foundation*, 71–73.

Decker, H. (1975). Sewage sod system saves time. *Weeds Trees & Turf*, *14*(6), 40–41.

Decker, H. (1989). Growing sod over plastic: Turf in five weeks. *Landscape Management*, *28*(7), 68,70.

Decker, H. (1991). Producing Sod on Plastic: Pros and Cons. *TurfNews [ASPA]*, *14*(3), 14,16,18.

Decker, H. (2001). Producing Sods over Plastic in Soilless Media. In J. Janick (Ed.), *Horticultural Reviews* (1st ed., Vol. 27, pp. 317–351). Wiley. https://doi.org/10.1002/9780470650813.ch8

Dover, G. (1999). History of the Magnum Harvester-helping to overcome labor obstacles: A long, difficult—But rewarding—Commitment. *TurfNews [TPI]*, *23*(1).

Dover, S. (2000). New Installers/Harvesters Make the Big Roll a Major Factor for the Future. *TurfNews [TPI]*, *24*(4), 48,50.

Dudeck, A., & Peacock, C. (1992). Shade and Turfgrass Culture. In D. Waddington, R. Carrow, & R. Shearman (Eds.), *Agronomy Monographs* (pp. 269–284). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr32.c8

Dunn, J., Ervin, E., & Fresenburg, B. (2002). Turf Performance of Mixtures and Blends of Tall Fescue, Kentucky Bluegrass, and Perennial Ryegrass. *HortScience*, *37*(1), 214–217. https://doi.org/10.21273/HORTSCI.37.1.214

Engel, R., & Trout, J. (1980). Seedling Competition of Kentucky Bluegrass, Red Fescue, Colonial Bentgrass, and Temporary Grasses. In J. B. Beard (Ed.), *Proceedings of The Third International Turfgrass Research Conference* (pp. 379–389). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2135/1974.proc3rdintlturfgrass.c44

Fédération Internationale de Football Association. (2022). *FIFA World Cup 2022 Qatar Regulations*. Fédération Internationale de Football Association. https://digitalhub.fifa.com/m/2744a0a5e3ded185/original/FIFA-World-Cup-Qatar-2022-Regulations_EN.pdf

Folck, A., Bigelow, C., Jiang, Y., & Patton, A. (2023). Genotypic variation in germination rate, seedling vigor, and seed phenotype of Kentucky bluegrass cultivars. *Crop Science*, *63*(5), 3065–3078. https://doi.org/10.1002/csc2.21045

Friell, J., Watkins, E., Horgan, B., & Cavanaugh, M. (2017). Sod Strength Characteristics of 51 Cool-Season Turfgrass Mixtures. *Agronomy Journal*, *109*(4), 1749–1757.

Gardner, W. (1988). Water movement in soils. *USGA Green Section Record*, *26*(2), 23–27.

Gibeault, V., Autio, R., Spaulding, S., & Youngner, V. (1980). Mixing turfgrasses controls Fusarium blight. *California Agriculture*, *34*(10), 11–12.

Głąb, T., Szewczyk, W., & Kopeć-Jarosz, A. (2024). Comprehensive assessment of turfgrass wear tolerance: A study on mechanical and chemical traits. *Industrial Crops and Products*, *216*, 118837. https://doi.org/10.1016/j.indcrop.2024.118837

Gould, H. P., Lostetter, S. J., Samuelson, E. R., & Guyton, G. P. (2022). Lower Extremity Injury Rates on Artificial Turf Versus Natural Grass Playing Surfaces: A Systematic Review. *The American Journal of Sports Medicine*, *51*(6), 1615–1621. https://doi.org/10.1177/03635465211069562

Guevara, J., Bearss, R., Kilby, J., Rogers, E., Rogers, J., Fielder, R., Burbrink, C., Navarette, I., Williams, T., Dickson, K., & Sorochan, J. (2024, July 8). Assessing drainage mats for shallow profile football pitch. *ISEA 2024: The Engineering of Sport 15*.

Guinness World Records. (1998). *First retractable grass pitch*. https://www.guinnessworldrecords.com/world-records/113967-first-retractable-grass-pitch

Hsiang, T., Carey, K., He, B., & Eggens, J. (1997). Composition of mixtures of four turfgrass species four years after seeding under non-wear conditions. *International Turfgrass Society Research Journal*, *8*(Part 1), 671–679.

Ibbetson, C. (2019). Behind the scenes look at Tottenham's retractable pitch. *New Civil Engineer*. https://www.newcivilengineer.com/latest/behind-the-scenes-look-at-tottenhams-retractable-pitch-04-04-2019/

Las Vegas Raiders. (2020). FUNDamentals of Football: Allegiant Stadium's retractable field tray. *Raiders*. https://www.raiders.com/video/fundamentals-of-football-allegiant-stadiums-retractable-field-tray

Lehnert, R. (1993). Laying the groundwork for World Cup Soccer. *SportsTURF*, *9*(6), 8,11-13.

Li, D., Henderson, J., Tim Vanini, J., & Rogers, J. (2015). Research Tools and Technologies for Turfgrass Establishment. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, Use, and Management* (pp. 1189–1239). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr56.c31

McInnes, K., & Thomas, J. (2011). Water Storage in Putting Greens Constructed with United States Golf Association and Airfield Systems Designs. *Crop Science*, *51*(3), 1261–1267. https://doi.org/10.2135/cropsci2010.08.0498

McNitt, A., Middour, R., & Waddington, D. (1997). Development and Evaluation of a Method to Measure Traction on Turfgrass Surfaces. *Journal of Testing and Evaluation*, *25*(1), 99–107. https://doi.org/10.1520/JTE11329J

Minner, D., & Valverde, F. (2005). Performance of established cool-season grass species under simulated traffic. *International Turfgrass Society Research Journal*, *Part 1*, 393–397.

Niehaus, M. H. (1976). Effect of Cultivar, Seeding Rate, and Nitrogen Fertilization on Kentucky Bluegrass-Perennial Ryegrass Turf Mixtures[1]. *Agronomy Journal*, *68*(6), 955–957. https://doi.org/10.2134/agronj1976.00021962006800060028x

Odgaard, N. (2003). Seahawks Stadium: A natural for soccer match. *SportsTURF*, *19*(5), 24–25.

Proctor, C., Weisenberger, D., & Reicher, Z. (2015). Kentucky Bluegrass and Perennial Ryegrass Mixtures for Establishing Midwest Lawns. *HortScience*, *50*(1), 137–140. https://doi.org/10.21273/HORTSCI.50.1.137

Puhalla, J., Krans, J., & Goatley, M. (1999). *Sports Fields: A Manual for Design, Construction and Maintenance* (1st ed.). Ann Arbor Press.

Rieke, P., & Beard, J. B. (1969). Factors in Sod Production of Kentucky Bluegrass. *Proceedings of the First International Turfgrass Research Conference*, *1*, 514–521.

Ripley, T., & Indyk, H. (1993). *Turfing systems for Stadia* (US Patent 5 187 894).

Roberts, B., Decker, H., Ganahl, L., & Yarmark, E. (2001). Biosolid Residues as Soilless Media for Growing Creeping Bentgrass Sod. *HortTechnology*, *11*(3), 451–455. https://doi.org/10.21273/HORTTECH.11.3.451

Rogers, J., Stier, J., & Crum, J. (1993). Indoor turf/World Cup '94 soccer tournament project update. *TurfNews [ASPA]*, *17*(6), 18–19.

Rogers, J., Stier, J., Crum, J., Krick, T., & Vanini, J. (1997). The Sports Turf Management Research Program at Michigan State University. In *Safety in American Football* (pp. 132–144). ASTM.

Rogers, J., Stier, J., Crum, J., & Rieke, P. (1995). Indoor turf/ World Cup '94 project update. *Proceedings of the 65th Annual Michigan Turfgrass Conference*, *24*, 227–229.

Rogers, J., Stier, J., Crum, J., Rieke, P., & Lawson, T. (1994). Facts sheet for natural turfgrass pitch at Pontiac Silverdome for US Cup '93/World Cup '94. *Proceedings of International Symposium on Soccer Field*, 89-91,167-170.

Rose-Harvey, K., McInnes, K., & Thomas, J. (2012). Water Flow Through Sand-based Root Zones Atop Geotextiles. *HortScience*, *47*(10), 1543–1547. https://doi.org/10.21273/HORTSCI.47.10.1543

Sherratt, P., & Street, J. (2005). Establishment rate and traffic tolerance of cool-season grasses for sports fields. *International Turfgrass Society Annexe - Technical Papers*, *10*, 67–68.

Sorochan, J., & Rogers, J. (2001). The Effect of Mulch Type for Turfgrass Establishment within a Refined Wood Fiber Mat over Plastic. *Journal of Environmental Horticulture*, *19*(2), 61–64. https://doi.org/10.24266/0738-2898-19.2.61

SportsTURF. (1997). Giants Stadium tests a new field-on-wheels. *SportsTURF*, 18-20,22.

State Farm Stadium. (2024). State Farm Stadium: About. *State Farm Stadium*. https://www.statefarmstadium.com/about

Stewart, B., Vanderford, J., Wells, D., & Philley, H. (2017). Growing sand-based sod using transported sand over native soil. *International Turfgrass Society Research Journal*, *13*, 1–6. https://doi.org/10.2134/itsrj2016.10.0847

Stier, J., Koeritz, E., & Garrison, M. (2008). Timing the Establishment of Kentucky Bluegrass: Perennial Ryegrass Mixtures for Football Fields. *HortScience*, *43*(1), 240–244. https://doi.org/10.21273/HORTSCI.43.1.240

Tretter, J. (2024). *Only Natural Grass Can Level The NFL's Playing Field | NFLPA*. https://nflpa.com/posts/only-natural-grass-can-level-the-nfls-playing-field

Young, T., Mann, R., & Spring, C. (2022). Use of plastic geocellular modules as a replacement gravel layer for natural turf rootzones. *International Turfgrass Society Research Journal*, *14*(1), 339–351. https://doi.org/10.1002/its2.99

# CHAPTER 2: EVALUATING KENTUCKY BLUEGRASS AND PERENNIAL RYEGRASS SEEDING RATIOS FOR SOD GROWN ON PLASTIC PRODUCTION


## Abstract

Sod grown on plastic (SOP) is a popular choice among sports field managers due to its dense rooting system, allowing play immediately after installation. Kentucky bluegrass (KBG; *Poa pratensis* L.) is a commonly used cool-season turfgrass species in sod production and sports fields. However, growing a pure KBG SOP is challenging due to KBG's slow germination rate, rendering the initial stages of sod production vulnerable to soil erosion. The researchers hypothesized that incorporating perennial ryegrass (PRG; *Lolium perenne* L.) can stabilize the soil while KBG is in its germination phase. Although KBG and PRG mixtures have been studied in sports fields, the optimal KBG and PRG ratio for sod production has yet to be explored. Thus, the objective of this study was to evaluate the harvestability of cool-season SOP seeded with varying KBG and PRG seeding ratios. The study was conducted at the Hancock Turfgrass Research Center in East Lansing, MI in the summers of 2023 and 2024. The experimental design was a randomized complete block design with 3 replications. Six KBG: PRG seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16 and 0:100), which all followed a pure live seeding rate of 3 seeds cm $^{-2}$. Four months after seeding, turfgrass cover, sod tensile strength, sod shear strength, stand composition, and shoot density were measured. Even a small addition of PRG, as low as 2%, significantly increased turfgrass cover, although it did not impact shear strength. The 84:16 seeding ratio resulted in a 58% increase in tensile strength compared to the 100:0 ratio and was identified as the recommended mix. The findings of this study enable sod farmers to produce harvestable sod in just four months, enhancing profitability and meeting the growing demand for high-quality sod for sports fields.

## Introduction

Kentucky bluegrass (*Poa pratensis* L.; KBG) is the dominant cool-season turfgrass species in sod production across the northern United States and southern Canada – valued for its sod-forming abilities due to its rhizomatous growth habit (Rieke & Beard, 1969). It is commonly grown through conventional sod production, where sod is grown directly in the native soil. This process typically entails clearing, plowing, harrowing, grading, and seeding the land (Daniel, 1962; Johanningsmeier, 1965; Beard, 1969). However, it can take up to 24 months to ensure that rhizomes are fully knitted together (Decker, 2001). During harvest, a sod cutter removes the sod from the soil by cutting through the roots, which in turn causes root damage. Consequently, prompt care and immediate transplanting are essential for successful establishment (Beard, 1969; Decker, 2001)

With the adoption of sand-based construction for sports fields and golf courses, challenges arise when conventional sod grown on native organic soils is transplanted onto a sand-based rootzone. This difference in soil porosity can lead to issues with soil layering, negatively impacting root growth and field performance (Gardner, 1988).

An alternative to conventional sod production is sod grown on plastic, where turfgrass is cultivated on a thin layer of growing medium placed atop a plastic sheet (Decker, 1975, 1991). This method significantly reduces production time by encouraging roots to interweave upon contact with the plastic (Decker, 1989). Additionally, it allows for the use of a compatible growing medium, which helps prevent soil layering issues. During harvest, the sod can be rolled without damaging the roots, thereby minimizing transplant shock when installing it onto a sand-based sports field (Decker, 1975).

Despite its advantages, sod grown on plastic production poses unique challenges, particularly when producing KBG sod. These production areas are typically sloped to facilitate surface drainage, which increases the risk of soil erosion, especially on sandy soils. KBG generally requires 7 to 14 days to germinate (Braun et al., 2023; Folck et al., 2023), leaving the soil highly susceptible to erosion during this period due to the lack of an established root system.

Perennial ryegrass (*Lolium perenne* L.; PRG), with its rapid germination, as early as three days (Braun et al., 2023), offers a potential solution to this problem. PRG has been used to control soil erosion (Brown et al., 2010) and could stabilize the sandy soil layer during KBG establishment in sod grown on plastic production. Therefore, researchers have hypothesized that incorporating small amounts of PRG into the seed mix could address erosion concerns in sod grown on plastic production.

The development of turf-type PRG has allowed the use of KBG/PRG seed mixtures (Niehaus, 1976), which are now commonly used in sports fields to improve genetic diversity and resilience to environmental stresses (Dunn et al., 2002). These mixtures have demonstrated superior turf cover and traffic tolerance compared to monocultures (Brede & Duich, 1984; Stier et al., 2008). However, the fast establishment and competitiveness of PRG can impede the establishment of KBG, potentially affecting the long-term composition of a KBG-dominated stand (Engel & Trout, 1980, Braun et al., 2023; Folck et al., 2023).

Studies have shown that when KBG and PRG are sown simultaneously, KBG often comprises only 3% to 30% of the tillers, despite accounting for 50% to 59% of the viable seeds in the mixture (Larsen et al., 2004). For instance, a 50:50 KBG-to-PRG mixture by weight resulted in a composition of 67% PRG and 27% KBG after four years (Hsiang et al., 1997). Gibeault et al. (1980) found that that an 85:15 KBG-to-PRG mixture by weight resulted in an approximate 50:50 plant ratio after three years. Proctor et al. (2015) observed that seeding ratios with a high proportion of KBG (80% to 90% KBG by weight) shifted to a stand dominated by more than 95% KBG within two years. Ratios lower in KBG followed a similar trend but required three years to reach a comparable composition.

These research studies highlight the importance of selecting appropriate seeding ratios when aiming to produce KBG-dominated sod, as the initial seeding ratio has a significant influence on the turfgrass composition. However, it is important to note that most of these studies on seeding ratios have relied on weight-based measurements, which, as Brede & Duich (1984) observed, can be influenced by variations in seed size, purity, and germination rates among turfgrass species and cultivars (Christians et al., 1979). Such differences in pure live seed can affect the consistency and reliability of these studies. Therefore, calculating seeding ratio and rates based on PLS is recommended to ensure more accurate and repeatable results.

Although the benefits of KBG-PRG mixtures for sports fields are well-documented, their application in sod grown on plastic remains limited. To address this gap, a research study was conducted at Michigan State University from 2023 to 2024 to determine the optimal KBG-PRG seeding ratio for sod grown on plastic. The objectives of the study were: (1) to evaluate the surface stability and harvestability of cool-season sod grown on plastic seeded with varying KBG-PRG ratios, and (2) to provide a seeding ratio recommendation for sod farmers producing cool-season sod grown on plastic.

## Methodology

*Experimental design*

This research was conducted in 2023 (8 June to 8 September) and 2024 (24 May to 19 August) at the Hancock Turfgrass Research Center, East Lansing, MI. The experimental design was a randomized complete block design with 3 replications (Figure 1). There were six Kentucky bluegrass: perennial ryegrass seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16 and 0:100) which followed a pure live seeding rate of 3 seeds $cm^{-2}$. Each plot measured 1.5 m × 1.5 m.

*Site preparation, establishment and maintenance*

DuraEgde clay (DuraEdge Products, Inc., USA) was used as the base and laser-graded to a 1% slope to facilitate proper drainage (Figure 2a). A 3-mil, 70% white Poly Film plastic sheet (Ginegar Plastics Ltd.) was then laid over the laser-graded clay base (Figure 2b). A 2.5 cm sand layer (Table 1) was topdressed using Turfco Mete-R-Matic IV Topdresser (Turfco®, Minnesota, USA) on top of the plastic sheet (Figure 2c). Each plot was hand-seeded with 'Benchmark' perennial ryegrass (Table 2) according to specified seeding ratios (Table 3). Vitality HD Sports 2.0 coated with Xalt (Vitality™, Maryland, USA) and EGS Tri Ryegrass (Landmark Seeds Inc., Oregon, USA) were the seeding blends used for KBG and PRG, respectively (Tables 1 & 2). Then, a starter fertilizer (12-23-12) (Harell's LLC, Florida, USA) was applied at a rate of 9.8 g phosphorus (P) $m^{-2}$ along with urea stabilized with N-(n-butyl) thiophosphoric triamide (46-0-0) (J.R. Simplot Company, California, USA) at a the rate of 4.9 g nitrogen (N) $m^{-2}$. After seeding the plots, the area was lightly raked with the backside of leaf rake. A cotton germination blanket (A.M. Leonard®, Ohio, USA) was placed over the area and the area was irrigated up to field capacity (Figure 2d). Once the grass germinated, the germination blanket was removed. The grass was consistently maintained at a mowing height of 3 cm using a push rotary mower

(Recycler® High Wheel Push Gas Lawn Mower, TORO®, USA), with clippings collected after each mowing. Nitrogen fertilizer was applied weekly at 1.2 g N $m^{-2}$ using granular urea (46-0-0) with a rotary spreader. The area was irrigated based on potential evapotranspiration, with total irrigation amounting to approximately 262 mm in 2023 and 358 mm in 2024 (Figure 3). Additional hand-watering or syringing was applied as needed to address dry spots.

| Rep | | | | | | |
|---|---|---|---|---|---|---|
| I | 3 | 1 | 5 | 4 | 2 | 6 |
| II | 1 | 4 | 6 | 2 | 3 | 5 |
| III | 4 | 2 | 5 | 1 | 6 | 3 |

1.5 m × 1.5 m

| Trt no. | % Kentucky bluegrass | % Perennial ryegrass |
|---|---|---|
| **1** | 100 | 0 |
| **2** | 98 | 2 |
| **3** | 96 | 4 |
| **4** | 92 | 8 |
| **5** | 86 | 16 |
| **6** | 0 | 100 |

**Figure 1.** Plot layout.

**Table 1.** 'Vitality HD Sports 2.0' Kentucky bluegrass (*Poa pratensis* L.) blend seed label[a].

| Variety | Purity (%) | Germination (%) |
|---|---|---|
| Bluebank | 12.42 | 85.00 |
| Hampton | 12.41 | 85.00 |
| Fullback | 12.93 | 85.00 |
| - | 12.22 | 85.00 |
| | | |
| Other Crop | 0.00 | |
| Inert matter (Xalt seed coating product) | 50.56 | |
| Weed seed | 0.00 | |

[a] Vitality™, Maryland, USA

**Table 2.** 'EGS Tri' perennial ryegrass (*Lolium perenne* L.) blend seed label[a].

| Variety | Purity (%) | Germination (%) |
|---|---|---|
| Majesty | 33.22 | 90.00 |
| Spark | 33.17 | 90.00 |
| Salinas II | 31.59 | 90.00 |
| | | |
| Other Crop | 0.22 | |
| Inert matter | 1.80 | |
| Weed seed | 0.00 | |

[a] Landmark Seeds Inc., Oregon, USA.


**Figure 2**. Sod grown on plastic establishment process at Hancock Turfgrass Research Center, East Lansing, Michigan in June 2023. (a) DuraEgde was used as the base and laser-graded to a 1% slope. (b) A white plastic was laid down on the area. (c) Sand (2.5 cm depth) was topdressed on top of the plastic sheet. (d) A germination blanket was placed over the area, followed by thorough irrigation.

**Table 3.** Particle size distribution of sand used for sod grown on plastic establishment in Hancock Turfgrass Research Center, East Lansing, Michigan, USA – 2023.

| Description | Very Coarse Sand | Coarse Sand | Medium Sand | Fine Sand | Very Fine Sand | Silt + Clay |
|---|---|---|---|---|---|---|
| Size (mm) | 2.0-1.0 | 1.0-0.5 | 0.5-0.25 | 0.25-0.15 | 0.15-0.05 | < 0.05-0.002 |
| Percent (%) | 12.1 | 19.6 | 40.5 | 19.7 | 2.1 | 0.3 |

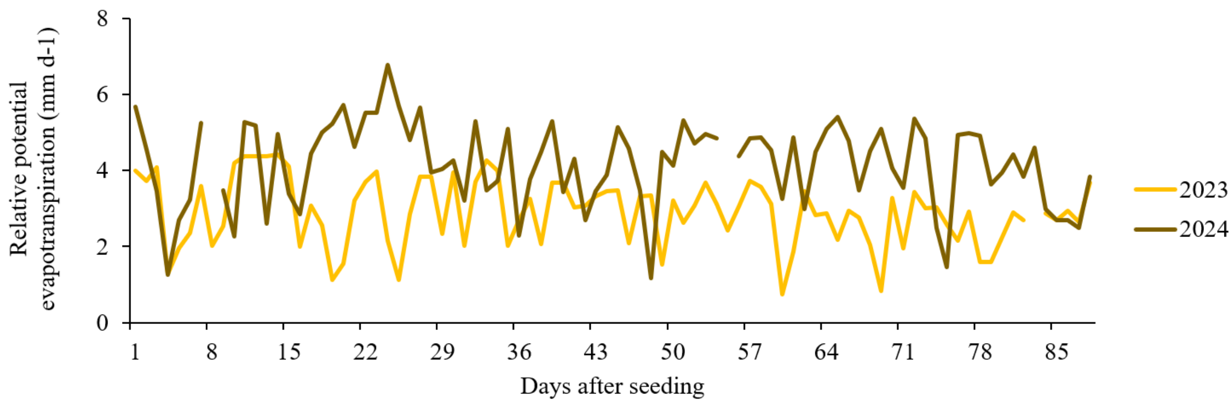


**Figure 3.** Relative potential evapotranspiration recorded at the Hancock Turfgrass Research Center, East Lansing, Michigan, USA, in 2023 and 2024. Data were obtained from the Michigan Automated Weather Network (MAWN) (https://mawn.geo.msu.edu/station.asp?id=htc).

*Data collection*

Turfgrass cover, sod tensile strength, sod shear strength, stand composition and shoot density were measured at 4 months after seeding. To quantify percent turfgrass cover, a modified method based on Richardson et al. (2001) was used. Overhead images of each plot were captured using a Canon PowerShot SX730HS (Canon, USA) digital camera set to macro mode with the following settings: ISO 800, F4.0, and a shutter speed of 1/250s. The images were analyzed using ImageJ software (Schneider et al., 2012). To measure sod tensile strength, a CHATILLON® DFE-200 Digital Force Gauge (AMETEK®, USA) was used to measure peak force value while pulling a 0.3 m × 0.5 m sod piece apart with a Calrochan Sod Puller (Sorochan et al., 1999; Sorochan & Rogers, 2000). Sod shear strength was determined from getting the average of three measurements using a Turf-Tec Shear Strength Tester (Turf-Tec International, Florida, USA). To measure stand composition and shoot density, three 2.5 cm × 2.5 cm (6.25 $cm^2$) samples were collected from each plot. Shoots were individually counted and identified as either KBG or PRG.

*Statistical analysis*

All data were analyzed using R software (R Core Team, 2024). Seeding ratio, year and seeding ratio × year were treated as fixed effect, whereas replication was considered as a random effect. The analysis of variance (ANOVA) was conducted to examine the significance of fixed effects and their interactions. Post hoc mean separation tests were conducted using Fisher's protected Least Significant Difference when F tests were significant at $\alpha=0.05$.

## Results and discussion

*Turfgrass cover*

As the slowest germinating grass species (Braun et al., 2023), KBG requires a long time to establish a mature turfgrass stand. While the addition of PRG has been shown to promote rapid turfgrass cover in sports fields (Brede & Duich, 1984), its role in sod grown on plastic production has not yet been studied. Hence, this study aimed to assess the impact of incorporating PRG into the seed mix and its effect on the turfgrass cover of a cool-season sod grown on plastic.

The ANOVA results revealed a significant interaction between seeding ratio and year for turfgrass cover (Table 4). In 2023, no significant differences were observed among seeding ratio treatments. In 2024, significant differences were observed among seeding ratio treatments. The pure KBG treatment had the lowest turfgrass cover, but the addition of 2% to 16% PRG led to an average increase of 57% in turfgrass cover (Figure 4). These findings suggest that even a small inclusion of PRG – as low as 2% – can significantly improve turfgrass cover compared to a pure KBG sod grown on plastic.

The ability of PRG to rapidly establish likely explains its contribution to improved turfgrass cover (Braun et al., 2023). PRG germinates within 3 to 5 days, whereas KBG requires 7 to 14 days to germinate, even when improved cultivars are used (Braun et al, 2023; Folck et al., 2023). The differences in turfgrass cover observed in KBG plots between 2023 and 2024 (Figure 4), with lower cover in 2023, can be attributed to variations in precipitation during the first two weeks of establishment (Figure 5). In 2023, only a single precipitation event occurred, delivering 2.5 mm of rainfall. In contrast, 2024 experienced seven precipitation events, with the highest delivering 8 mm of rainfall. This variation in early rainfall likely influenced KBG establishment.

Excessive precipitation during the germination stage can cause soil erosion, washing away seeds and resulting in reduced turfgrass cover in pure KBG plots.

PRG has been recommended for pastures and lawns to mitigate establishment challenges (Blaser et al., 1956) and has also been used effectively for soil erosion control (Brown et al., 2010). By stabilizing the soil surface and providing rapid cover, PRG reduces the risk of seed washout and promotes better establishment. This benefit was demonstrated by the improved turfgrass cover achieved when PRG is incorporated into the seed mix, highlighting its value as a beneficial component in KBG-dominated sod grown on plastic production.

**Table 4.** Analysis of variance testing for the effect of Kentucky bluegrass (*Poa pratensis* L.; KBG) and perennial ryegrass (*Lolium perenne* L.; PRG) seeding ratios and year on the turfgrass cover, sod tensile strength, sod shear strength, shoot density and stand composition of a sod grown on plastic harvested at 4 months after seeding in East Lansing, Michigan, USA – 2023 and 2024.

| **Effect** | **Turfgrass cover** | **Sod tensile strength** | **Sod shear strength** | **Shoot density** | **Stand composition** | |
|---|---|---|---|---|---|---|
| | | | | | **KBG** | **PRG** |
| Ratio (R) | *** | *** | ns | * | *** | *** |
| Year (Y) | *** | *** | *** | *** | ns | ns |
| R × Y | * | ns | ns | * | ns | ns |

ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

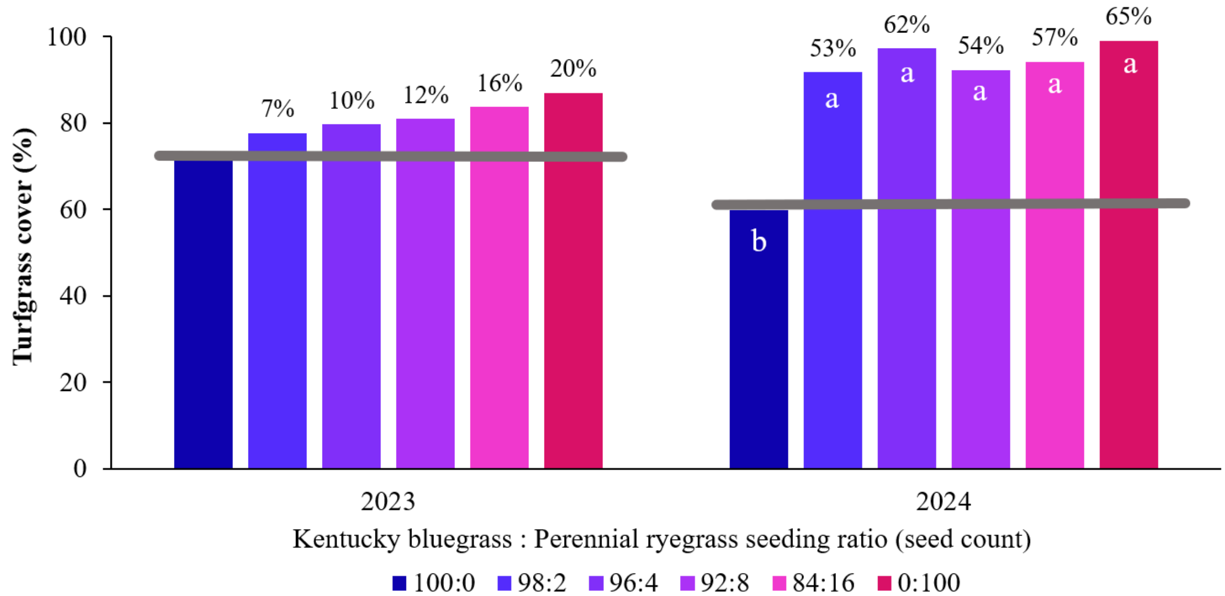


**Figure 4**. Interaction of Kentucky bluegrass and perennial ryegrass seeding ratio and year on the percent turfgrass cover of sod grown on plastic, harvested 4 months after seeding in East Lansing, Michigan, USA – 2023 and 2024. Within each year, means followed by the same letters are not statistically different based on Fisher's Protected Least Significant Difference test ($\alpha$ = 0.05). The gray line represents the pure Kentucky bluegrass (100:0) mean for that year. Percentages above the bars indicate the increase in turfgrass cover compared to the 100:0 treatment.

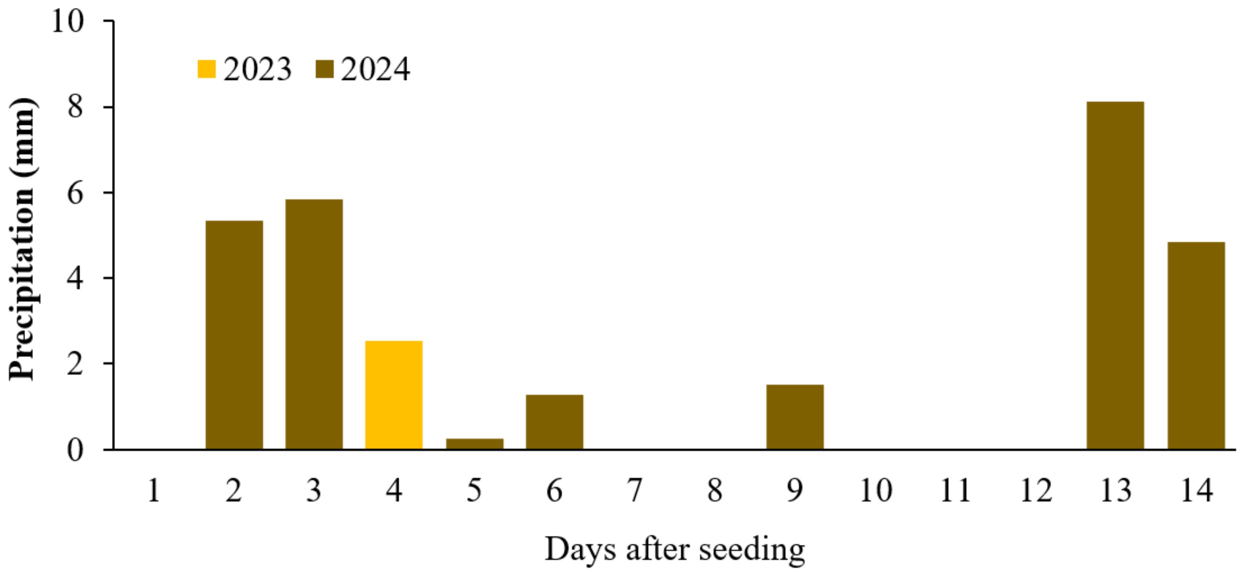


**Figure 5.** Total precipitation (mm) during the first two weeks of turfgrass establishment at the Hancock Turfgrass Research Center, East Lansing, Michigan, USA, in 2023 and 2024. Data sourced from Michigan State University Enviro-Weather: https://mawn.geo.msu.edu/station.asp?id=htc.

*Sod strength*

This study aimed to address this knowledge gap by evaluating two types of sod strength: tensile strength and shear strength. Tensile strength refers to the resistance of sod to being pulled apart and is commonly used to assess the harvestability of sod. It quantifies the breaking point of the sod during handling, influenced by its weight (Li et al., 2015). In contrast, shear strength measures the stability of the sod surface (Li et al., 2015).

The ANOVA results revealed no significant interaction between seeding ratio and year for sod tensile or shear strength (Table 4). As a result, the main effects of seeding ratio and year were further examined. Both factors influenced sod tensile strength. All seeding ratio treatments exceeded 17.2 kg · force – the minimum threshold for harvestable, mature KBG sod (Table 5a), as measured using the Calrochan Sod Puller (Sorochan & Rogers, 2000). Pure KBG (100:0) exhibited the lowest tensile strength, while pure PRG (0:100) demonstrated significantly higher tensile strength, 80 percent greater than pure KBG. The addition of 2, 4 or 8 percent PRG did not significantly increase tensile strength. However, the inclusion of 16 percent PRG resulted in a 58 percent increase in tensile strength (Figure 6a). These findings suggest that adding 16 percent PRG to the seed mix can significantly increase sod tensile strength, benefiting sod

Additionally, tensile strength was higher in 2023 compared to 2024 (Figure 6a). This difference may be attributed to the higher evapotranspiration observed in 2024 compared to 2023 (data sourced from Michigan State University Enviro-Weather). Although irrigation was based on evapotranspiration estimates, the timing and application of supplemental irrigation may have been inadequate, potentially leading to drought stress that affected sod strength development. farmers by improving the harvestability and durability of cool-season sod grown on plastic.

Regarding shear strength, the ANOVA showed no significant interaction between seeding ratio and year. However, year had a significant effect (Table 4), with sod shear strength being higher in 2023 than in 2024 (Figure 6b). The seeding ratio did not significantly influence shear strength (Table 4), although the addition of PRG numerically increased shear strength. This increase, however, was not statistically significant (Figure 6b). These findings suggest that adding PRG has a limited effect on improving surface stability. Other factors, such as soil type and soil moisture, have been shown to influence shear strength (Henderson et al., 2005). Since this study used the same soil type and maintained similar water content throughout, no differences in shear strength were observed.

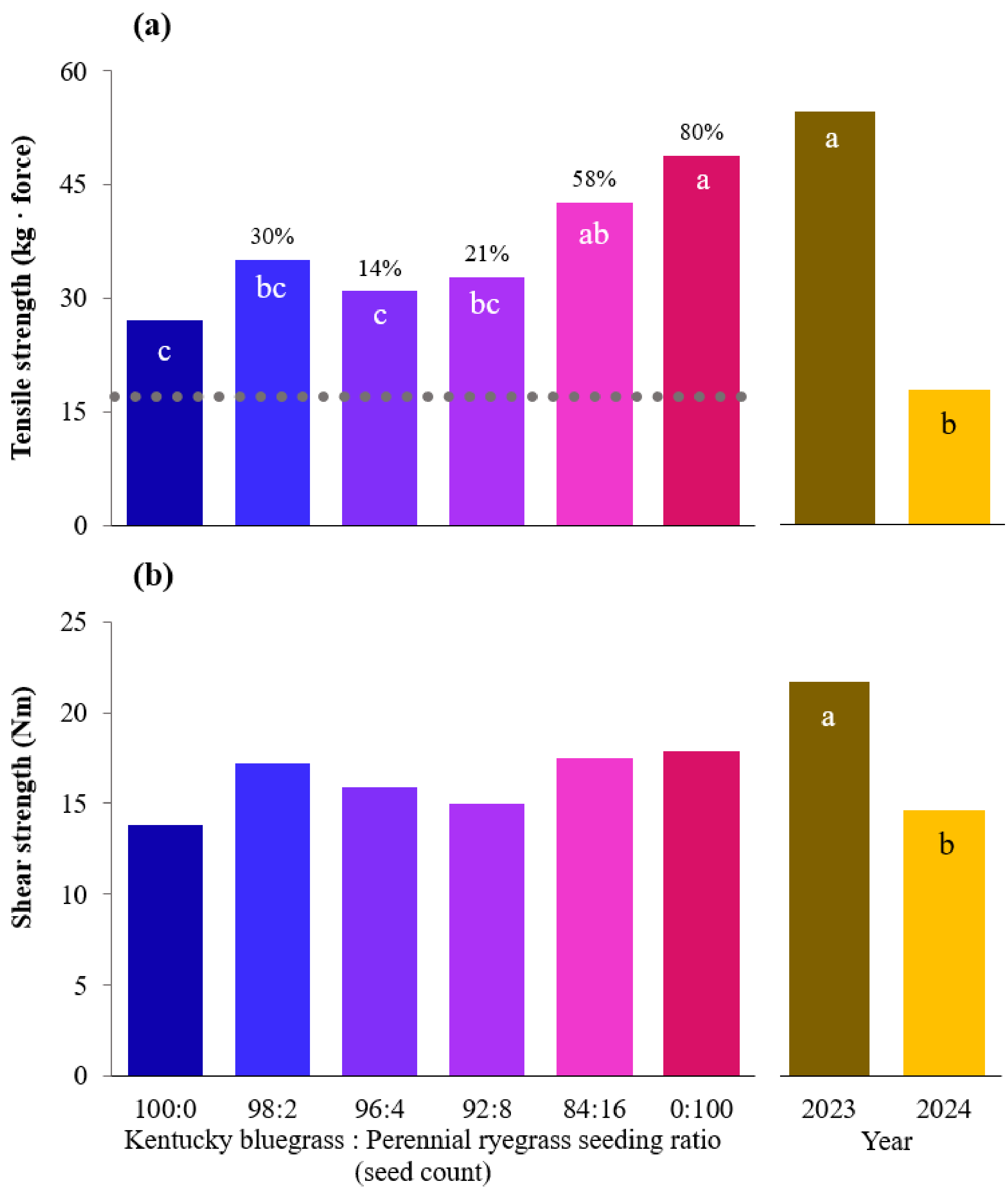


**Figure 6.** Effect of Kentucky bluegrass and perennial ryegrass seeding ratio and year on **(a)** sod tensile strength and **(b)** shear strength of sod grown on plastic, harvested 4 months after seeding in East Lansing, Michigan, USA – 2023 and 2024. Within seeding ratio and year, means followed by the same letters are not statistically different based on Fisher's Protected Least Significant Difference test ($\alpha = 0.05$). Dotted gray line represents the minimum tensile strength value to harvest a mature Kentucky bluegrass sod (Sorochan & Rogers, 2000).

*Turfgrass stand composition and density*

Turfgrass stand composition is a critical consideration, particularly when a sod farmer aim to produce KBG-dominated sod. PRG is highly competitive and often outcompetes KBG when grown together (Engel & Trout, 1980; Hsiang et al., 1997; Larsen et al., 2004). To address this issue, seeding ratios of 85:15 KBG-to-PRG and lower were examined in this study. This decision was informed by findings from Gibeault et al. (1980), who demonstrated that an 85:15 KBG-to-PRG ratio by weight resulted in an approximate 50:50 KBG-to-PRG shoot ratio after three years – a balance considered ideal for mature turfgrass stands. However, in this study, pure live seed counts were used instead of weight-based measurements, which may influence turfgrass stand composition.

No interaction between species composition and year was detected, indicating consistent trends across both 2023 and 2024 (Table 4). As a result, pooled data from both years were analyzed. Contamination of KBG in pure PRG plots and PRG in pure KBG plots was observed, but the overall stand composition generally aligned with the seeding ratios (Table 5). Nevertheless, KBG plant counts were slightly lower than anticipated based on initial viable seed counts (Table 5). This aligns with findings from Larsen et al. (2004) who reported that simultaneous sowing of KBG and PRG often results in deviations from the initial seed ratios, with higher PRG and lower KBG plant counts than expected. In this study, an 84:16 KBG-to-PRG seeding ratio resulted in a 56:44 KBG-to-PRG shoot ratio – a stand composition closely resembling the ideal 50:50 ratio (Gibeault et al., 1980).

**Table 5.** Effect of Kentucky bluegrass (*Poa pratensis* L.; KBG) and perennial ryegrass (*Lolium perenne* L.; PRG) seeding ratios and year on the shoot density and stand composition of a sod grown on plastic harvested at 4 months after seeding in East Lansing, Michigan, USA – 2023 and 2024.

| **Seeding ratio** [a] | **Shoot density** [b] | | **Species composition** [b] | |
|---|---|---|---|---|
| (KBG:PRG) | 2023 | 2024 | Kentucky bluegrass (%) | Perennial ryegrass (%) |
| 100:0 | 18.1 | 33.7 ab [c] | 90.7 a | 9.3 c |
| 98:2 | 15.7 | 11.6 c | 82.8 a | 17.2 c |
| 96:4 | 14.3 | 27.2 abc | 75.6 ab | 24.4 bc |
| 92:8 | 12.5 | 19.3 bc | 69.7 ab | 30.3 bc |
| 84:16 | 14.5 | 24.3 bc | 55.8 b | 44.2 b |
| 0:100 | 13.2 | 41.8 a | 9.9 c | 90.1 a |

[a] based on 3 pure live seeds $cm^{-2}$.

[b] shoots were individually counted from 6.25 $cm^2$ samples and identified as either KBG or PRG.

[c] Within a column, means followed by the same letters are not statistically different based on Fisher's Protected Least Significant Difference test ($\alpha = 0.05$).

*Perennial ryegrass sod grown on plastic*

One unexpected finding in this study was that the pure PRG plots exhibited the highest turfgrass cover (Figure 4) and tensile strength (Figure 5a) among all seeding ratio treatments. PRG has a bunch-type growth habit – characterized by a lack of extensive rhizomes and stolons but a strong primary rooting system – which limits its ability to be harvested as big roll sod. However, sod grown on plastic production has proven effective for turfgrass species with a bunch-type growth habit, such as tall fescue (*Festuca arundinacea*) (Decker, 1991). Given that the 0:100 treatment exceeded the minimum threshold for harvesting mature sod using the Calrochan Sod Puller (Sorochan & Rogers, 2000), further research could explore refining the establishment techniques for PRG sod grown on plastic.

## Conclusions

This study demonstrated the effectiveness of incorporating PRG into KBG-dominated sod grown on plastic, offering valuable insights for cool-season sod farmers. While KBG remains popular for its familiarity and proven performance, adding PRG to the seed mix provides several advantages. A KBG/PRG mixture enables farmers to produce more resilient sod in less time as early as 4 months, meeting the growing demand for high-quality sod for sports fields and improving profitability. The addition of 16 percent PRG was found to provide an optimal balance, enhancing turfgrass cover and achieving acceptable sod strength. This mix also resulted in a 56:44 KBG-to-PRG shoot ratio, which is close to the ideal 50:50 ratio (Gibeault et al., 1980). Further research is needed to explore the long-term performance of these mixtures in sports fields. Additionally, there is a need to explore the potential of PRG sod grown on plastic and refine methods to further expedite sod production.

## REFERENCES


Beard, J. B., Rieke, P., & Astwood, J. (1969). Sod production of Kentucky bluegrass. *Proceedings of the First International Turfgrass Research Conference*, *1*, 509–513.

Braun, R. C., Courtney, L., & Patton, A. (2023). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, *63*(3), 1613–1627. https://doi.org/10.1002/csc2.20936

Brede, A., & Duich, J. (1984). Establishment characteristics of Kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. *Agronomy Journal*, *76*, 6. https://doi.org/10.2134/agronj1984.00021962007600060004x

Brown, R., Percivalle, C., Narkiewicz, S., & DeCuollo, S. (2010). Relative Rooting Depths of Native Grasses and Amenity Grasses with Potential for Use on Roadsides in New England. *HortScience*, *45*(3), 393–400. https://doi.org/10.21273/HORTSCI.45.3.393

Christians, N. E., Wilkinson, J. F., & Martin, D. P. (1979). Variations in the Number of Seeds per Unit Weight Among Turfgrass Cultivars[1]. *Agronomy Journal*, *71*(3), 415–419. https://doi.org/10.2134/agronj1979.00021962007100030008x

Christians, N., Patton, A., & Law, Q. (2016). *Fundamentals of Turfgrass Management, Fifth Edition* (1st ed.). Wiley. https://doi.org/10.1002/9781119308867

Daniel, W. (1962). Sod production. *Proceedings of 1962 Turf Conference Sponsored by the Midwest Regional Turf Foundation*, 71–73

Decker, H. (1975). Sewage sod system saves time. *Weeds Trees & Turf*, *14*(6), 40–41.

Decker, H. (1989). Growing sod over plastic: Turf in five weeks. *Landscape Management*, *28*(7), 68,70.

Decker, H. (2001). Producing Sods over Plastic in Soilless Media. In J. Janick (Ed.), *Horticultural Reviews* (1st ed., Vol. 27, pp. 317–351). Wiley. https://doi.org/10.1002/9780470650813.ch8

Decker, H. (1991). Producing Sod on Plastic: Pros and Cons. *TurfNews [ASPA]*, *14*(3), 14,16,18.

Dunn, J., Ervin, E., & Fresenburg, B. (2002). Turf Performance of Mixtures and Blends of Tall Fescue, Kentucky Bluegrass, and Perennial Ryegrass. *HortScience*, *37*(1), 214–217. https://doi.org/10.21273/HORTSCI.37.1.214

Engel, R. & Trout, J. (1980). Seedling Competition of Kentucky Bluegrass, Red Fescue, Colonial Bentgrass, and Temporary Grasses. In J. B. Beard (Ed.), *Proceedings of The Third International Turfgrass Research Conference* (pp. 379–389). American Society of

Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2135/1974.proc3rdintlturfgrass.c44

Folck, A., Bigelow, C., Jiang, Y., & Patton, A. (2023). Genotypic variation in germination rate, seedling vigor, and seed phenotype of Kentucky bluegrass cultivars. *Crop Science*, *63*(5), 3065–3078. https://doi.org/10.1002/csc2.21045

Gibeault, V., Autio, R., Spaulding, S., & Youngner, V. (1980). Mixing turfgrasses controls Fusarium blight. *California Agriculture*, *34*(10), 11–12.

Henderson, J., Crum, J., Wolff, T., & Rogers, J. (2005). Effects of Particle Size Distribution And Water Content at Compaction On Saturated Hydraulic Conductivity and Strength of High Sand Content Root Zone Materials. *Soil Science*, *170*(5), 315–324. https://doi.org/10.1097/01.ss.0000169906.02485.7f

Hsiang, T., Carey, K., He, B., & Eggens, J. (1997). Composition of mixtures of four turfgrass species four years after seeding under non-wear conditions. *International Turfgrass Society Research Journal*, *8*(Part 1), 671–679.

Johanningsmeier, E. (1965). Sod production. *6th Turfgrass Conference Proceedings*, 63–66.

Larsen, S., Andreasen, C., & Kristoffersen, P. (2004). Differential Sowing Time of Turfgrass Species Affects the Establishment of Mixtures. *Crop Science*, *44*(4), 1315–1322. https://doi.org/10.2135/cropsci2004.1315

Li, D., Henderson, J., Tim Vanini, J., & Rogers, J. (2015). Research Tools and Technologies for Turfgrass Establishment. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, Use, and Management* (pp. 1189–1239). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr56.c31

Michigan State University. (2024). *Michigan State University Enviro-Weather*. https://mawn.geo.msu.edu/station.asp?id=htc

Niehaus, M. (1976). Effect of Cultivar, Seeding Rate, and Nitrogen Fertilization on Kentucky Bluegrass-Perennial Ryegrass Turf Mixtures[1]. *Agronomy Journal*, *68*(6), 955–957. https://doi.org/10.2134/agronj1976.00021962006800060028x

Proctor, C., Weisenberger, D., & Reicher, Z. (2015). Kentucky Bluegrass and Perennial Ryegrass Mixtures for Establishing Midwest Lawns. *HortScience*, *50*(1), 137–140. https://doi.org/10.21273/HORTSCI.50.1.137

Puhalla, J., Krans, J., & Goatley, M. (1999). *Sports Fields: A Manual for Design, Construction and Maintenance* (1st ed.). Ann Arbor Press.

R Core Team. (2024). *R: A language and environment for statistical computing. R Foundation for Statistical Computing* [Computer software]. https://www.R-project.org/

Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying Turfgrass Cover Using Digital Image Analysis. *Crop Science*, *41*(6), 1884–1888. https://doi.org/10.2135/cropsci2001.1884

Rieke, P., & Beard, J. B. (1969). Factors in Sod Production of Kentucky Bluegrass. *Proceedings of the First International Turfgrass Research Conference*, *1*, 514–521.

Sorochan, J., Calhoun, R., & Rogers, J. (1999). Apparatus to measure turfgrass sod strength. *1999 Annual Meeting Abstracts [ASA/CSSA/SSSA]*, *91*, 137.

Sorochan, J., & Rogers, J. (2000). Measuring sod strength of Kentucky bluegrass and Supina bluegrass. *TurfGrass TRENDS*, *8*(9), 6–9.

Stewart, B., Vanderford, J., Wells, D., & Philley, H. (2017). Growing sand-based sod using transported sand over native soil. *International Turfgrass Society Research Journal*, *13*, 1–6. https://doi.org/10.2134/itsrj2016.10.0847

Stier, J., Koeritz, E., & Garrison, M. (2008). Timing the Establishment of Kentucky Bluegrass: Perennial Ryegrass Mixtures for Football Fields. *HortScience*, *43*(1), 240–244. https://doi.org/10.21273/HORTSCI.43.1.240

Turfgrass Producers International. (2006). *Guideline Specifications to Turfgrass Sodding*. Turfgrass Producers International.

# CHAPTER 3: OPTIMIZING PERENNIAL RYEGRASS SEEDING RATES FOR SOD GROWN ON PLASTIC PRODUCTION


## Abstract

Perennial ryegrass (*Lolium perenne* L.; PRG) is a popular cool-season turfgrass for sports fields due to its rapid germination and high wear tolerance. However, its bunch-type growth habit prevents it from being harvested as big roll sod, restricting its establishment to seeding. However, previous research has demonstrated that PRG big roll sod can be grown using sod produced on plastic. This production method involves growing sod on a growing medium over a plastic sheet instead of directly in soil, promoting dense rooting that enables bunch-type turfgrasses to form cohesive sod. While PRG seeding rates are established for lawns, roughs and overseeding, no guidelines exist for sod grown on plastic production. Thus, this study aimed to identify the optimal seeding rate for PRG sod grown on plastic production. The research was conducted at Michigan State University, East Lansing, MI, during the summers of 2023 and 2024, using a randomized complete block design with three replications. Four seeding rates – 1.5, 3, 6, and 9 pure live seeds (PLS) $cm^{-2}$ – were evaluated. Turfgrass cover and sod tensile and shear strength were assessed at 4, 6, 8, 10, and 12 weeks after seeding (WAS), respectively. Results showed that the 1.5 PLS $cm^{-2}$ rate had lower turfgrass coverage and shear strength compared to the higher seeding rates at 4 WAS. However, the 1.5 and 3 PLS $cm^{-2}$ rates exhibited greater tensile strength than the 6 and 9 PLS $cm^{-2}$ rates at 12 WAS. These results displayed the trade-off between turfgrass cover, stability and sod durability and 1.5 and 3 PLS $cm^{-2}$ was identified as the optimal rate. This study provides valuable insights for sod producers, enabling faster establishment of cool-season sod for sports fields.

## Introduction

Perennial ryegrass (*Lolium perenne* L.*;* PRG) is a widely used cool season turfgrass species for sports fields due to its rapid germination rate and high wear tolerance (Braun et al., 2023; Głąb et al., 2024). However, its bunch-type growth habit – characterized by a lack of rhizomes and stolons but possessing a strong primary rooting system limits its ability to be harvested as a big roll sod. Consequently, perennial ryegrass is typically established from seed or used as an overseed to provide rapid green coverage to maintain field aesthetics and playability.

However, recent research (Chapter 1) has demonstrated that perennial ryegrass sod can be grown using a method known as 'sod grown on plastic production'. In this method, sod is cultivated on a growing medium over a plastic sheet rather than directly in soil. Primary roots spread laterally across the plastic surface, knitting the growing medium into a cohesive mat (Decker, 1975, 1991). Sod that was grown on plastic has gained popularity for sports fields, because it can be grown with a compatible growing medium that minimizes soil layering issues (Decker, 1975). It can also be easily harvested by rolling, without damaging the roots, allowing it to establish quickly in a new location (Decker, 2001) and making the installed sod ready for play within days. Additionally, sod grown on plastic production has proven to be effective for turfgrass species with bunch-type growth habit such as tall fescue (*Festuca arundinacea*) (Decker, 1991).

Given that perennial ryegrass is the fastest germinating cool-season grass (Braun et al., 2023), this method could significantly accelerate cool-season sod production. However, seeding rate recommendations for perennial ryegrass vary widely, ranging from 19 to 39 g $m^{-2}$ (Brede & Dunfield, 1988). Understanding the optimal seeding rate is crucial because it has an effect on establishment. Low seeding rates can lead to thin establishment and vulnerable to weed encroachment  (Brede & Dunfield, 1988). High seeding rates during establishment can create a dense canopy layer which lead to damping off  (Madison, 1966). In a research study examining Kentucky bluegrass (*Poa pratensis* L.) on sand-based fields, lower seeding rates promoted longer root growth, while higher seeding rates produced shorter root growth but improved turf quality (Kim, 2024).

Research on various cool-season grasses grown for sod on sandy soils found that higher seeding rates facilitated faster establishment with greater turfgrass cover but resulted in lower sod tensile strength.  Subsequently, lower seeding rates led to stronger sod (Shildrick, 1982). However, some research studies have reported that seeding rate had minimal impact on sod strength, growth rate, or transplant success (Braun et al., 2021a, 2021b). Therefore, to optimize perennial ryegrass sod grown on plastic production, practical questions remain such as the ideal seeding rate to produce harvestable sod in the shortest timeframe.

To determine the optimum seeding rate for perennial ryegrass sod grown on plastic, a research study was conducted at Michigan State University from 2023 to 2024. The objectives of this research were: (1) To evaluate the harvestability of perennial ryegrass sod grown on plastic with varying seeding rates and (2) provide a seeding rate recommendation to sod farmers for perennial ryegrass sod grown on plastic. Specifically, to compare turfgrass cover, sod shear strength, and sod tensile of perennial ryegrass sod grown on plastic using different seeding rates and harvesting dates.

## Methodology

*Experimental design*

This experiment was conducted in 2023 (8 June to 8 September) and 2024 (24 May to 19 August) at the Hancock Turfgrass Research Center, East Lansing, Michigan, USA. The experimental design was a two-factor randomized complete block with 3 replications. Four seeding rates were evaluated: 1.5, 3, 6 and 9 pure live seeds [PLS] cm$^{-2}$ which was harvested at 4, 6, 8, 10 and 12 weeks after seeding (WAS). Each plot measured 0.9 m × 0.9 m (Figure 1).

*Site preparation, establishment and maintenance*

DuraEgde clay (DuraEdge Products, Inc., USA) was used as the base and laser-graded to a 1% slope to facilitate proper drainage (Figure 2a). A 3-mil, 70% white Poly Film plastic sheet (Ginegar Plastics Ltd.) was then laid over the laser-graded clay base (Figure 2b). A 2.5 cm sand layer (Table 1) was topdressed using Turfco Mete-R-Matic IV Topdresser (Turfco®, Minnesota, USA) on top of the plastic sheet (Figure 2c). Each plot was hand-seeded with 'Benchmark' perennial ryegrass (Table 2) according to specified seeding rates (Table 3). Then, a starter fertilizer (12-23-12) (Harell's LLC, Florida, USA) was applied at a rate of 9.8 g phosphorus (P) m$^{-2}$ along with urea stabilized with N-(n-butyl) thiophosphoric triamide (46-0-0) (J.R. Simplot Company, California, USA) at a the rate of 4.9 g nitrogen (N) m$^{-2}$. After seeding the plots, the area was lightly raked with the backside of leaf rake. A cotton germination blanket (A.M. Leonard®, Ohio, USA) was placed over the area and the area was irrigated up to field capacity. (Figure 2d). Once the grass germinated, the germination blanket was removed. The grass was consistently maintained at a mowing height of 3 cm using a push rotary mower (Recycler® High Wheel Push Gas Lawn Mower, TORO®, USA), with clippings collected after each mowing. Nitrogen fertilizer was applied weekly at 1.2 g N m$^{-2}$ using granular urea (46-0-0) with a rotary spreader. The area was irrigated based on potential evapotranspiration, with total irrigation amounting to approximately 262 mm in 2023 and 358 mm in 2024 (Figure 3). Additional hand-watering or syringing was applied as needed to address dry spots.

*Data collection*

Turfgrass cover, shear strength, and tensile strength were measured at harvest dates: 4, 6, 8, 10, and 12 weeks after seeding. To quantify percent turfgrass cover, overhead images of each plot were captured using a Canon PowerShot SX730HS (Canon, USA) digital camera set to macro mode, ISO 800, F4.0, and 1/250s. To quantify percent turfgrass cover, a modified method based on Richardson et al. (2001) was used. Overhead images of each plot were captured using a Canon PowerShot SX730HS (Canon, USA) digital camera set to macro mode with the following settings: ISO 800, F4.0, and a shutter speed of 1/250s. The images were analyzed using ImageJ software (Schneider et al., 2012). Sod tensile strength was measured using a CHATILLON® DFE-200 Digital Force Gauge (AMETEK, USA) by pulling apart a 0.3 m ft x 0.5 m sod piece with a Calrochan Sod Puller (Sorochan et al., 1999, Sorochan & Rogers, 2000) . Sod shear strength was determined as the average of three measurements using a Turf-Tec Shear Strength Tester (Turf-Tec International, Florida, USA)

*Statistical analysis*

All data were analyzed using R software (R Core, 2024). Each year was analyzed separately. Seeding rate, harvest dates and seeding rate × harvest date were treated as fixed effect, whereas replication was considered as a random effect. The analysis of variance (ANOVA) was conducted to examine the significance of fixed effects and their interactions. Post hoc mean separation tests were conducted using Fisher’s protected Least Significant Difference when F tests were significant at $\alpha$=0.05.

N

0.9 m × 0.9 m

| Weeks after seeding |
| --- |
| seeds cm$^{-2}$ |

| Rep | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| I | 4 | 12 | 8 | 6 | 4 | 8 | 12 | 10 | 6 | 10 |
| | 1.5 | 9 | 6 | 1.5 | 3 | 9 | 1.5 | 6 | 3 | 9 |
| | 12 | 8 | 10 | 4 | 6 | 12 | 10 | 6 | 8 | 4 |
| | 6 | 1.5 | 3 | 9 | 6 | 3 | 1.5 | 9 | 3 | 6 |
| II | 10 | 6 | 6 | 12 | 8 | 10 | 12 | 10 | 8 | 4 |
| | 3 | 9 | 6 | 1.5 | 1.5 | 6 | 9 | 1.5 | 6 | 3 |
| | 8 | 4 | 12 | 10 | 4 | 6 | 8 | 12 | 4 | 6 |
| | 9 | 1.5 | 3 | 9 | 6 | 1.5 | 3 | 6 | 9 | 3 |
| III | 8 | 6 | 8 | 6 | 12 | 6 | 4 | 10 | 8 | 4 |
| | 9 | 6 | 1.5 | 1.5 | 9 | 3 | 6 | 1.5 | 6 | 3 |
| | 4 | 10 | 12 | 10 | 12 | 6 | 8 | 4 | 10 | 12 |
| | 1.5 | 3 | 6 | 9 | 3 | 9 | 3 | 9 | 6 | 1.5 |

**Figure 7**. Plot layout.


**Figure 8**. Sod grown on plastic establishment process at Hancock Turfgrass Research Center, East Lansing, Michigan in June 2023. (a) DuraEgde was used as the base and laser-graded to a 1% slope. (b) A white plastic was laid down on the area. (c) Sand (2.5 cm depth) was topdressed on top of the plastic sheet. (d) A germination blanket was placed over the area, followed by thorough irrigation.

**Table 6.** Particle size distribution of sand used for sod grown on plastic establishment in Hancock Turfgrass Research Center, East Lansing, Michigan, USA – 2023.

| Description | Very Coarse Sand | Coarse Sand | Medium Sand | Fine Sand | Very Fine Sand | Silt + Clay |
|---|---|---|---|---|---|---|
| Size (mm) | 2.0-1.0 | 1.0-0.5 | 0.5-0.25 | 0.25-0.15 | 0.15-0.05 | < 0.05-0.002 |
| Percent (%) | 12.1 | 19.6 | 40.5 | 19.7 | 2.1 | 0.3 |

**Table 7.** 'Benchmark' perennial ryegrass (*Lolium perenne* L.) seed label – Landmark Seed Company, Oregon, USA.

| Variety | Purity (%) | Germination (%) |
|---|---|---|
| Benchmark | 99.60 | 90.00 |
| Other Crop | 0.00 | |
| Inert matter | 0.40 | |
| Weed seed | 0.00 | |

**Table 8.** Perennial ryegrass (*Lolium perenne* L.) seeding rate treatments.

| pure live seeds $cm^{-2}$ | $g\ m^{-2}$ [a] |
|---|---|
| 1.5 | 24 |
| 3 | 49 |
| 6 | 98 |
| 9 | 146 |

[a] calculated using the seed label (Table 2) and manual count of number of seeds $gram^{-1}$.

## Results and discussion

*Turfgrass cover*

The ANOVA revealed a significant interaction between seeding rate and harvest date for turfgrass cover (Table 9). In 2023, at 4 WAS, turfgrass cover ranged from 80% at the lowest seeding rate (1.5 PLS $cm^{-2}$) to 100% at the highest seeding rate (9 PLS $cm^{-2}$). By 6 WAS, no significant differences in turfgrass cover were observed across the seeding rates (Figure 9a). In 2024, the lowest seeding rate (1.5 PLS $cm^{-2}$) resulted in the lowest turfgrass cover at both 4 and 6 WAS, with values of 38 percent and 80 percent, respectively. However, by 8 WAS, no significant differences in turfgrass cover were observed among seeding rates (Figure 9b). Although 1.5 PLS $cm^{-2}$ treatment lagged during early establishment, it eventually caught up with the other treatments.

The differences in turfgrass cover observed at 4 and 6 weeks after seeding (WAS) between years (Figure 9) were likely due to drought stress resulting from higher temperatures during the first four weeks of 2024. Evapotranspiration during this period reached 86 mm and 118 mm in 2023 and 2024, respectively (data sourced from Michigan State University Enviro-Weather). Although irrigation was based on ET, the timing of water application may not have been precise enough to meet the required amount, especially given the limited water-holding capacity of the 2.5 cm sand root zone.

**Table 9.** Analysis of variance testing for the effects of seeding rate, harvest date and their interaction on the turfgrass cover, shear strength and tensile strength of a perennial ryegrass sod grown on plastic in East Lansing, Michigan, USA – 2023 and 2024.

| | Turfgrass cover (%) | | Tensile strength (kg · force) | | Shear strength (Nm) | |
|---|---|---|---|---|---|---|
| | 2023 | 2024 | 2023 | 2024 | 2023 | 2024 |
| Seeding rate (S) | | | | | | |
| 1.5 PLS $cm^{-2}$ | 92.3 | 81.3 | 11.9 | 11.9 | 7.7 b [a] | 7.6 |
| 3 PLS $cm^{-2}$ | 96.3 | 97.9 | 12.6 | 10.0 | 11.2 a | 8.1 |
| 6 PLS $cm^{-2}$ | 98.1 | 97.8 | 12.4 | 8.6 | 11.4 a | 8.4 |
| 9 PLS $cm^{-2}$ | 98.2 | 97.9 | 10.3 | 6.6 | 11.5 a | 7.7 |
| *p-value* | *** | *** | ** | *** | *** | ns |
| Harvest date (H) | | | | | | |
| 4 weeks after seeding | 93.1 | 82.9 | 3.7 | 0.0 | 6.0 d | 4.6 |
| 6 weeks after seeding | 98.5 | 93.0 | 9.3 | 8.1 | 8.5 c | 7.4 |
| 8 weeks after seeding | 95.8 | 95.5 | 13.2 | 14.4 | 10.8 b | 8.6 |
| 10 weeks after seeding | 97.9 | 98.6 | 14.9 | 12.0 | 13.3 a | 9.7 |
| 12 weeks after seeding | 95.8 | 98.8 | 18.1 | 12.0 | 13.7 a | 9.6 |
| *p-value* | ** | *** | *** | *** | *** | *** |
| S × H | *** | *** | * | *** | ns | * |

[a] Within a column, means followed by the same letter are not significantly different according to Fisher's protected Least Significant Difference ($p \geq 0.05$).
ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

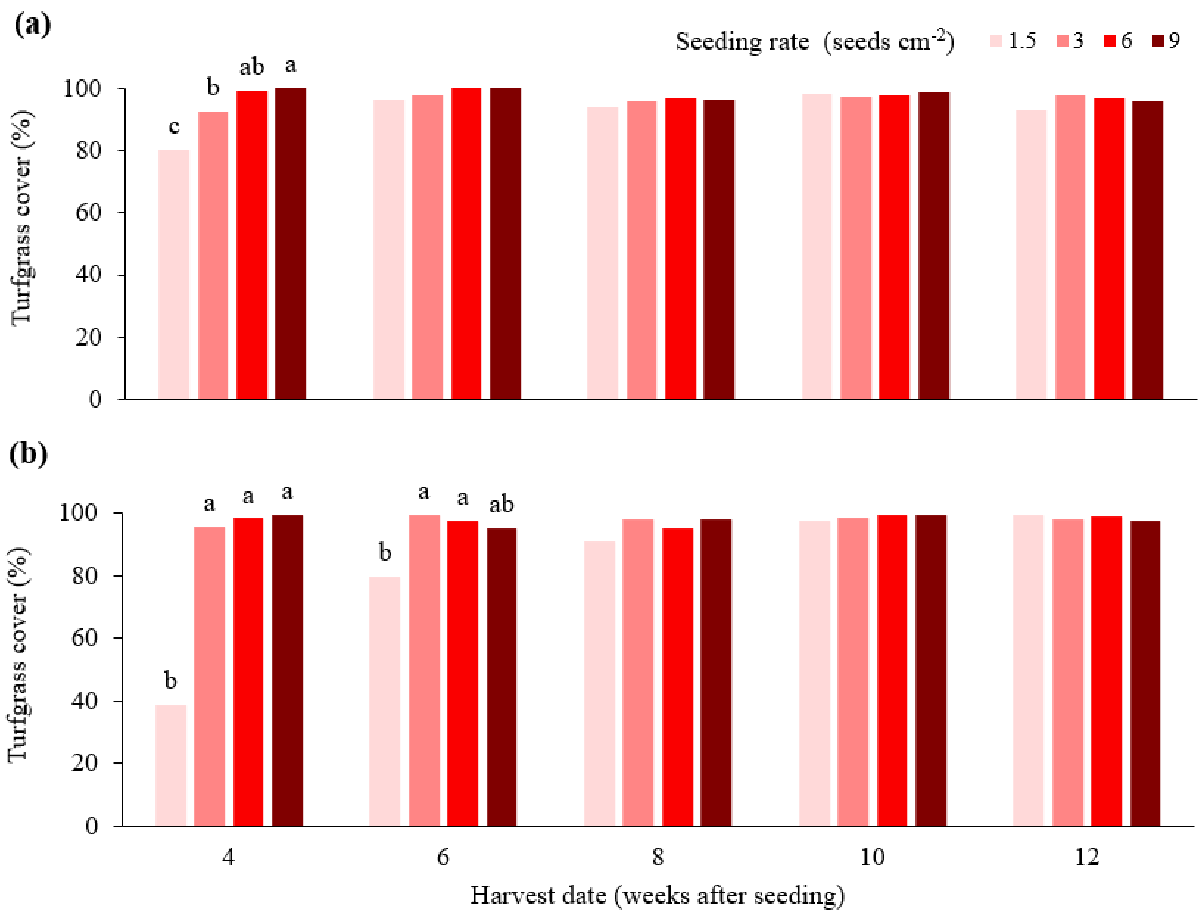


**Figure 9.** Effect of seeding rate on the turfgrass cover of a perennial ryegrass sod grown on plastic across various harvest dates in **(a)** 2023 and **(b)** 2024 – East Lansing, Michigan, USA. Means followed by the same letter are not significantly different according to Fisher's protected Least Significant Difference ($p \geq 0.05$).

*Sod shear strength*

In 2023, no significant interaction was found, thus the main effects were examined. Both seeding rate and harvest date significantly influenced shear strength (Table 9). The 1.5 PLS $cm^{-2}$ treatment showed the lowest shear strength, 48 percent lower than the other seeding rate treatments, while the remaining seeding rates did not differ (Table 9). Regarding harvest dates, shear strength was lowest at 4 WAS and increased until it plateaued between 10 and 12 WAS (Table 9).

In 2024, a significant interaction between seeding rate and harvest date was observed for shear strength (Table 9). At 4 WAS, the 9 PLS $cm^{-2}$ treatment had the highest shear strength (6.7 Nm), followed by 3 and 6 PLS $cm^{-2}$ (5 Nm), and 1.5 PLS $cm^{-2}$ showing the lowest (1.7 Nm). At 8 WAS, 3 PLS $cm^{-2}$ recorded the highest shear strength (10.7 Nm), followed by 1.5 PLS $cm^{-2}$ (8 Nm) and 6 PLS $cm^{-2}$ (7.3 Nm), while 9 PLS $cm^{-2}$ had the lowest (6.67 Nm). No significant differences were observed among seeding rates at 6, 10, and 12 WAS (Figure 10).

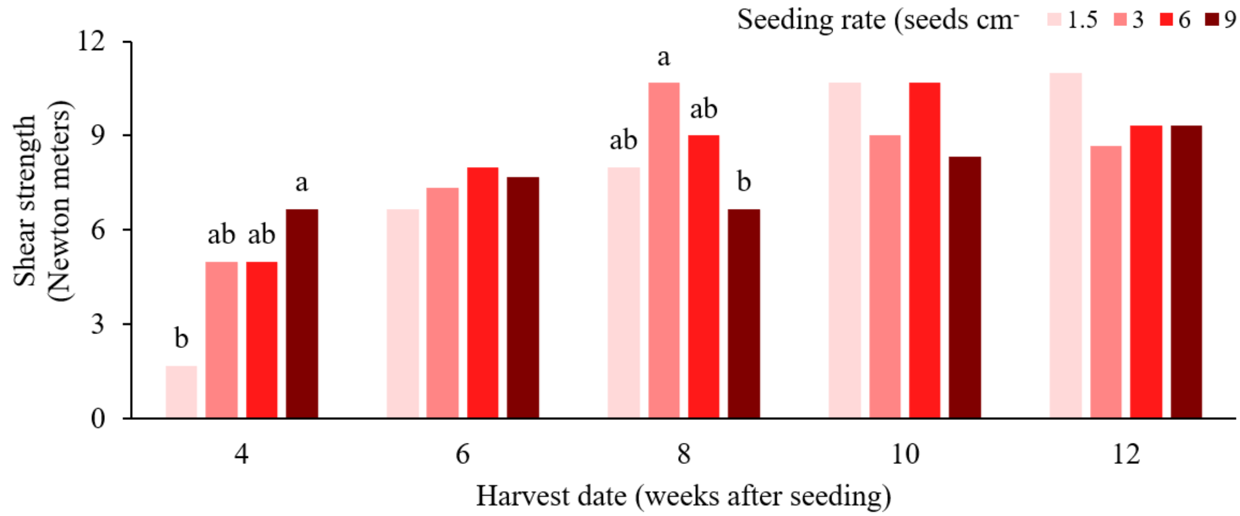


**Figure 10**. Effect of seeding rate on the shear strength of a perennial ryegrass sod grown on plastic across various harvest dates in 2024 – East Lansing, Michigan, USA. Means followed by the same letter are not significantly different according to Fisher's protected Least Significant Difference ($p \geq 0.05$).

*Sod tensile strength*

The ANOVA indicated a significant interaction between seeding rate and harvest date for tensile strength in 2023 and 2024. In 2023, tensile strength measurements at 4 WAS showed that sod grown with 1.5 PLS $cm^{-2}$ was not harvestable, while the 3 and 6 PLS $cm^{-2}$ treatments achieved the highest tensile strength at 6.1 kg and 5.4 kg, respectively. By 8 WAS, the 1.5 PLS $cm^{-2}$ treatment produced the strongest sod, followed by 3 and 6 PLS $cm^{-2}$, with 9 PLS $cm^{-2}$ showing the lowest tensile strength. At 12 WAS, sod tensile strength was highest in the 3 and 6 PLS $cm^{-2}$ treatments, followed by 1.5 PLS $cm^{-2}$, with 9 PLS $cm^{-2}$ having the lowest value (Figure 11a).

In 2024, none of the seeding rate treatments produced harvestable sod at 4 WAS (Figure 11b), likely due to elevated temperatures during the early establishment phase (Figure 9). Additionally, greater variability in sod tensile strength was observed between seeding rate treatments in 2024 compared to 2023, possibly due to the higher temperatures in 2024 (3117.4 GDD, base 32°F) compared to 2023 (3201.5 GDD, base 32°F). By 6 WAS, the 6 PLS $cm^{-2}$ treatment exhibited the highest tensile strength, followed by 1.5 and 3 PLS $cm^{-2}$, with 9 PLS $cm^{-2}$ producing the lowest tensile strength. At 8 WAS, the 1.5 and 3 PLS $cm^{-2}$ treatments showed the highest tensile strength values, reaching a harvestable value while 6 and 9 PLS $cm^{-2}$ had lower tensile strength values. At 10 WAS, the 1.5 PLS $cm^{-2}$ treatment demonstrated the highest tensile strength, followed by 3 PLS $cm^{-2}$. By 12 WAS, 1.5 PLS $cm^{-2}$ recorded the highest tensile strength at 15.9 kg, whereas 9 PLS $cm^{-2}$ had the lowest at 7.4 kg (Figure 11b).

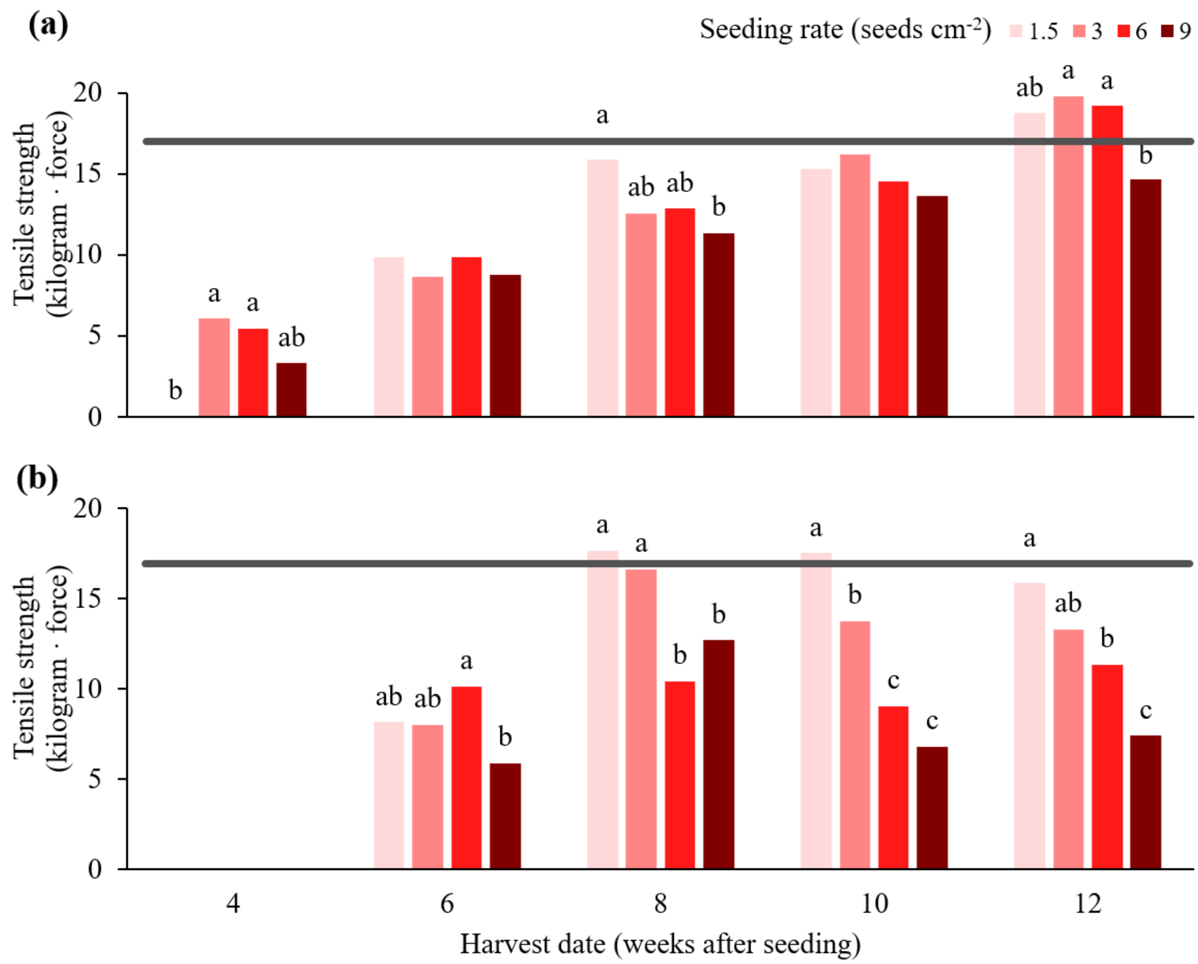


**Figure 11**. Effect of seeding rate on the tensile strength of a perennial ryegrass sod grown on plastic across various harvest dates in (a) 2023 and (b) 2024 – East Lansing, Michigan, USA. Means followed by the same letter are not significantly different according to Fisher's protected Least Significant Difference ($p \geq 0.05$). Gray line represents the minimum tensile strength value to harvest a mature Kentucky bluegrass sod (Sorochan & Rogers, 2000).

The observed trend revealed that lower seeding rates (1.5 and 3 PLS $cm^{-2}$) resulted in higher tensile strength values, whereas higher seeding rates (6 and 9 PLS $cm^{-2}$) led to reduced sod tensile strength. While this pattern does align with the findings of Shildrick (1982), who reported that higher seeding rates in Kentucky bluegrass, fescues (*Festuca* spp.), and bentgrass (*Agrostis* spp.) were associated with lower tensile strength, no significant differences were observed in that study. Similarly, Braun et al. (2021a) reported no significant impact of seeding rates on sod strength in Kentucky bluegrass and fine fescues. However, their study only considered seeding rates of 1, 2, and 3 PLS $cm^{-2}$, whereas this study evaluated a broader range (1.5, 3, 6, and 9 PLS $cm^{-2}$). By examining a wider range, this study captured variations in tensile strength, revealing trends that were not evident in previous research.

A potential explanation for this observation is that higher seeding rates may lead to increased competition among seedlings for nutrients, water, and space. Under stressed conditions, this competition could result in shorter, less developed root systems, which would negatively affect sod strength. In this study, roots from higher seeding rate treatments appeared smaller and exhibited a brownish hue, while roots from lower seeding rate treatments were thicker and had a healthier white color (Figure 12). Although this observation was not formally analyzed, it highlights the need for further research into how seeding rates influence root growth, particularly in sod grown on plastic production systems. Previous studies have shown that lower seeding rates promote longer root growth, while higher seeding rates tend to produce shorter roots during establishment (Kim, 2024).

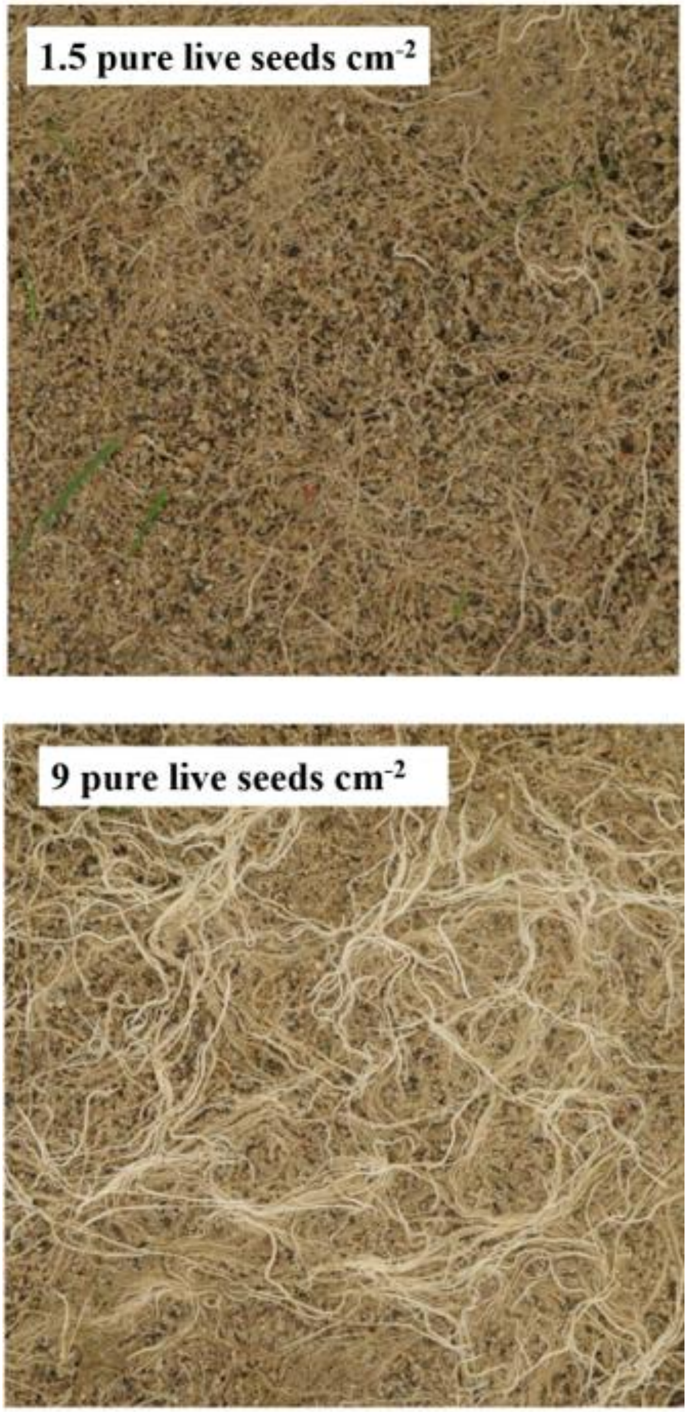


**Figure 12.** Rooting system of perennial ryegrass sod grown on plastic seeded at 1.5 and 9 PLS $cm^{-2}$ at 8 weeks after seeding – East Lansing, MI – 2023.

*Optimum seeding rate*

The goal of this study was to determine the optimal perennial ryegrass seeding rate for sod grown on plastic production systems. The lowest seeding rate (1.5 PLS $cm^{-2}$) resulted in reduced turfgrass cover during the early establishment phase, particularly within the first four to six weeks. However, it provided higher tensile strength starting at 8 WAS. (Figure 13). In contrast, higher seeding rates (6 and 9 PLS $cm^{-2}$) promoted greater turfgrass cover and stability during the early establishment phase (4 WAS) but resulted in decreased sod tensile strength during later growth stages (Figure 13). Based on these findings, a seeding rate of 3 PLS $cm^{-2}$ was identified as optimal, balancing adequate turfgrass cover at early establishment with sufficient sod tensile strength at 12 WAS. It is important to note that seeding rates higher than 3 PLS $cm^{-2}$ could lead to a decrease in tensile strength.

## Conclusions

These findings emphasize the trade-off between rapid establishment and sod durability. While high seeding rates (6 and 9 PLS $cm^{-2}$) may be advantageous for achieving rapid turfgrass coverage, it could limit the development of a cohesive sod structure. Conversely, 1.5 PLS $cm^{-2}$ can lead to less stable and sparse turfgrass cover during early growth stages, making the sod vulnerable to issues such as washout, but ultimately result in stronger sod by harvest. The 3 PLS $cm^{-2}$ seeding rates emerged as the optimal balance, providing adequate turfgrass coverage while maintaining acceptable sod tensile strength at 12 WAS. These insights are valuable for sod producers aiming to optimize both the speed of establishment and the quality of the final product for harvest and transplant, ensuring a reliable source of cool-season grass for sports field managers.

## REFERENCES


Braun, R., Courtney, L., & Patton, A. (2023). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, *63*(3), 1613–1627. https://doi.org/10.1002/csc2.20936

Braun, R., Watkins, E., Hollman, A., Mihelich, N., & Patton, A. (2021a). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, *113*(5), 4176–4189.

Braun, R., Watkins, E., Hollman, A., Mihelich, N., & Patton, A. (2021b). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: II. Management and shelf-life. *Agronomy Journal*, *113*(4), 3460–3474.

Brede, A., & Duich, J. (1984). Establishment characteristics of Kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. *Agronomy Journal*, *76*, 6. https://doi.org/10.2134/agronj1984.00021962007600060004x

Brede, D., & Dunfield, J. (1988). Seeding rate: Its effect on disease and weed encroachment. *Proceedings of the 42nd Northwest Turfgrass Conference*, 90–97.

Decker, H. (1975). Sewage sod system saves time. *Weeds Trees & Turf*, *14*(6), 40–41.

Decker, H. (1991). Producing Sod on Plastic: Pros and Cons. *TurfNews [ASPA]*, *14*(3), 14,16,18.

Decker, H. (2001). Producing Sods over Plastic in Soilless Media. In J. Janick (Ed.), *Horticultural Reviews* (1st ed., Vol. 27, pp. 317–351). Wiley. https://doi.org/10.1002/9780470650813.ch8

Głąb, T., Szewczyk, W., & Kopeć-Jarosz, A. (2024). Comprehensive assessment of turfgrass wear tolerance: A study on mechanical and chemical traits. *Industrial Crops and Products*, *216*, 118837. https://doi.org/10.1016/j.indcrop.2024.118837

Kim, K. (2024). Study on the Standard Seeding Rate for the Maturity Phase of the 2nd Year in Establishing Kentucky Bluegrass Turf in Landscape. *Weed & Turfgrass Science*, *13*(1), 1–14. https://doi.org/10.5660/WTS.2024.13.1.1

Madison, J. H. (1966). Optimum Rates of Seeding Turfgrasses[1]. *Agronomy Journal*, *58*(4), 441–443. https://doi.org/10.2134/agronj1966.00021962005800040024x

Michigan State University. (2024). *Michigan State University Enviro-Weather*. https://mawn.geo.msu.edu/station.asp?id=htc

R Core Team. (2024). *R: A language and environment for statistical computing. R Foundation for Statistical Computing* [Computer software]. https://www.R-project.org/

Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying Turfgrass Cover Using Digital Image Analysis. *Crop Science*, *41*(6), 1884–1888. https://doi.org/10.2135/cropsci2001.1884

Schneider, C., Rasband, W. & Eliceiri, K. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Shildrick, J. (1982). Mixtures and seed rates for sod production. *Journal of the Sports Turf Research Institute*, *58*, 76–95.

Sorochan, J., Calhoun, R., & Rogers, J. (1999). Apparatus to measure turfgrass sod strength. *1999 Annual Meeting Abstracts [ASA/CSSA/SSSA].*, *91*, 137.

Sorochan, J., & Rogers, J. (2000). Measuring sod strength of Kentucky bluegrass and Supina bluegrass. *TurfGrass TRENDS*, *8*(9), 6–9.

# CHAPTER 4: PERFORMANCE OF KENTUCKY BLUEGRASS AND PERENNIAL RYEGRASS SHALLOW PROFILE IN A CONTROLLED ENVIRONMENT


## Abstract

There is an increasing advocacy for natural turfgrass playing surfaces in professional sports due to higher injury rates linked to artificial turf compared to natural grass. However, light levels are significantly reduced or entirely lacking in domed stadiums, making artificial turf an easier option to manage. To address this, the “shallow turfgrass profile” consisting of sod grown on plastic over geocellular drainage modules, has been developed for easy installation and removal of natural turfgrass fields. Artificial lighting systems have been introduced to support turfgrass growth in domed stadiums. While the shallow turfgrass profile has been tested for surface playability, the performance of different Kentucky bluegrass (*Poa pratensis* L.; KBG) and perennial ryegrass (*Lolium perenne* L.; PRG) mixtures under artificial lighting remains untested. Thus, the objective of this study was to assess the effects of KBG: PRG seeding ratios on the visual turfgrass quality and surface performance within a shallow turfgrass profile under artificial lighting. In 2024, a study was conducted at the FIFA Indoor Pitch Simulator Facility in Knoxville, Tennessee. The study used a randomized complete block split-plot design with three replications. Traffic treatment, the whole-plot factor, included trafficked and non-trafficked conditions. Whereas the subplot factor consisted of six KBG: PRG seeding ratios (3 pure live seeds $cm^2$): 100:0, 98:2, 96:4, 92:8, 84:16, and 0:100. Weekly assessments showed that traffic significantly decreased turfgrass color and percent green cover as early as the second traffic application. However, seeding ratios performed similarly across parameters, including turfgrass color, percent green cover, maximum shear strength, and maximum displacement.

## Introduction

There is growing advocacy for natural turfgrass playing surfaces in professional sports due to an increase in injury rates associated with artificial turf compared to natural turfgrass (Gould et al., 2022). Organizations like the National Football League Players Association (Tretter, 2024) and the Fédération Internationale de Football Association (FIFA) have emphasized the importance of natural grass, with FIFA mandating that all World Cup matches be played on natural turfgrass playing surfaces (Fédération Internationale de Football Association, 2022).

Domed stadiums are often multi-use venues that host a wide range of events and activities that do not require a natural grass surface. To maximize profitability, these venues use artificial turf to keep their floors accessible as frequently as possible. Consequently, converting artificial turf fields into permanent natural grass surfaces is typically cost-prohibitive. In most cases, natural turfgrass fields in such settings tend to revert to artificial turf over time (SportsTURF, 1997). A more economical and practical alternative is the use of temporary natural grass playing surfaces. These systems can be installed over concrete, asphalt, or similar flooring and removed easily after matches, providing a feasible solution for events requiring natural grass (SportsTURF, 1997).

Palletized turf – also referred to as modular turf – is defined as turfgrass grown on 10 to 20 cm of root zone within a specific-size container (Li et al., 2015). The first palletized turf was used during 1993 United States Gold Cup (Germany vs. England). This system featured steel hexagonal frames filled with a sand:peat:loam mix (Ripley & Indyk, 1993; Rogers et al., 1993, 1995). Over time, the design evolved into square trays filled with sand-based rootzones, including the ITM system, Hummer Grass Tile System  and StrathAyr  (Li et al., 2015).

Palletized turf systems allowed the installation and removal of an entire field in a few days. However, the process remains time-consuming and labor-intensive. Additionally, adequate space is required to assemble the field outside the stadium prior to installation.

Since the 1993 United States Cup, advancements in sports turfgrass management have introduced more efficient systems. In 2000s, shallow turfgrass profile system – big roll sod grown on plastic laid directly over concrete, asphalt, or concert flooring – became a widely used technology for temporary fields in the United States (Odgaard, 2003). Sod grown on plastic is a type of sod cultivated on a plastic sheet, which allows the roots to bind together, forming a strong and dense rooting system (Decker, 2001). This production system also preserves the root apices during harvest, minimizing both harvest and transplant shock (Neel et al., 1978; Decker, 2001). As a result, creating a "ready-to-play" surface immediately after installation. This system can be installed and removed within a day. However, it is designed for short-term use, lasting no more than a week.

For the FIFA World Cup 2026, the temporary field needs to be maintained for five to six weeks, necessitating the need for watering; therefore, requiring a drainage system. Plastic geocellular modules, have been adopted as substitutes for traditional gravel layers due to their thin profile, portability, and ease of installation (Young et al., 2022). Research has demonstrated that these plastic geocellular modules perform comparably to standard gravel root zones used for golf course putting greens and sports fields (McInnes & Thomas, 2011; Rose-Harvey et al., 2012; Young et al., 2022). Guevara et al (2024) found that perennial ryegrass sod grown on plastic on top of Permavoid 85s geocellular drainage (Permavoid, Amsterdam, NL) met FIFA requirements for surface hardness and ball rebound height, further validating the efficacy of the geocellular drainage module for high-performance sports fields.

Another reason domed stadiums use artificial turf is the challenge of meeting agronomic needs, particularly light requirements. Light is essential for photosynthesis and is critical for plant growth and development (Dudeck & Peacock, 1992). However, light levels are significantly reduced or entirely lacking in domed stadiums, making artificial turf an easier option to manage.

The issue of insufficient light can be addressed using artificial lighting. Traditionally, high-pressure sodium (HPS) lighting systems have been used, as it provides both radiation and heat but are energy-intensive (Rogers, 1997). As an alternative, light-emitting diode (LED) technology offers several advantages over HPS. LEDs consume less energy, produce less heat, and have an adjustable light spectrum (Abélard & Galbrun, 2022). Research has shown that both HPS and LED systems can improve the performance of cool-season turfgrasses, such as perennial ryegrass (*Lolium perenne* L.; PRG), Kentucky bluegrass (*Poa pratensis* L.; KBG), and tall fescue (*Festuca arundinacea*), under shaded conditions by enhancing turfgrass quality, density, and wear tolerance. However, LEDs are preferred due to their lower energy consumption and customizable light spectrum, making them a more sustainable choice (Abélard & Galbrun, 2022).

Previous research (Chapter 1) evaluated various KBG: PRG seeding ratios, including an 84:16 mix and lower percentages of PRG, for their effects on sod production grown on plastic. While shallow turfgrass profiles incorporating Permavoid 85s geocellular drainage systems have shown potential for high-performance sports fields (Guevara et al., 2024), the performance of these systems with varying KBG-PRG mixtures under artificial lighting and trafficked conditions in a domed stadium environment remains unknown. To address this, a study was conducted in 2024 at the FIFA Indoor Pitch Simulator Facility at the University of Tennessee, Knoxville, to assess the effect of different KBG: PRG mixtures on surface performance and visual aesthetics within a shallow turfgrass profile system under controlled conditions.

## Materials and Methods

*Sod grown on plastic production*

In October 2022, the sod grown on plastic used in this study was established in Carolina Green Sod Farm (Concord, North Carolina, USA). A 2.5 cm layer of sand (Table 10) was topdressed over the 3-mil white plastic sheet. The plots were arranged in a randomized block design with three replications, each measuring 1.5 m × 1.5 m. There were six Kentucky bluegrass: perennial ryegrass seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16 and 0:100) which followed a pure live seeding rate of 3 seeds $cm^{-2}$.

The seeding blends used were Vitality HD Sports 2.0 coated with Xalt (Vitality, Maryland, USA) for KBG (Table 10) and EGS Tri Ryegrass (Landmark Seeds, Oregon, USA) for PRG (Table 11). Seeding was performed by hand, and slightly raked with the backside of the rake after to promote seed to soil contact. Then, a starter fertilizer (12-23-12) was applied at a rate of 9.8 g phosphorus (P) $m^{-2}$. A germination blanket was placed over the area, followed by thorough irrigation across the entire region. Once the grass germinated, the germination blanket was removed, and the grass was consistently maintained at a mowing height of 3 cm. and fertilized with 2.5 g $m^{-2}$ N (46-0-0) fertilizer per month. The sod was topdressed with sand (Table 10) throughout the growing period to achieve a rootzone of 5 cm.

The sod was intended to be transported to a controlled environment, the FIFA Indoor Pitch Simulator Facility at the University of Tennessee-Knoxville, for the study. However, delays in construction resulted in the sod remaining in place longer than anticipated. By July, nine months after establishment, the hot conditions in North Carolina had become detrimental to the growth of cool-season turfgrass. Consequently, the sod was harvested from Carolina Green

Sod Farm (Figure 13a) and transported via refrigerated truck to the Hancock Turfgrass Research Center in East Lansing, Michigan, USA (Figure 13b).

The sod remained on plastic at the Hancock Turfgrass Research Center from July 2023 to November 2023. During this time, it was maintained with a mowing height of 3 cm and received approximately 2.5 g $m^{-2}$ N (46-0-0) fertilizer per month. However, continued delays in the construction of the FIFA Indoor Pitch Simulator Facility, combined with the increasingly cold conditions in Michigan by November, required the sod to be relocated.

The sod was transported to the East Tennessee Research and Education Center (Knoxville, Tennessee), where it was maintained on plastic from November 2023 until the completion of the FIFA Indoor Pitch Simulator Facility in December 2023. During this period, the sod was regularly mowed to a height of 3 cm and received foliar applications of 2.5 g $m^{-2}$ N (46-0-0) fertilizer to maintain growth.

**Table 10**. Particle size distribution of sand used for sod grown on plastic establishment in Carolina Green Sod Farm, Indian Trail, North Carolina, USA – October 2022.

| Description | Fine Gravel | Very Coarse Sand | Coarse Sand | Medium Sand | Fine Sand | Very Fine Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|
| Size (mm) | >2.0 | 2.0-1.0 | 1.0-0.5 | 0.5-0.25 | 0.25-0.15 | 0.15-0.05 | 0.05-0.002 | <0.002 |
| Percent (%) | 3.6 | 26.2 | 43.9 | 18.4 | 4.3 | 1.7 | 0.7 | 1.4 |

**Table 11.** 'Vitality HD Sports 2.0' Kentucky bluegrass (*Poa pratensis* L.) blend seed label[a].

| Variety | Purity (%) | Germination (%) |
|---|---|---|
| Bluebank | 12.42 | 85.00 |
| Hampton | 12.41 | 85.00 |
| Bullback | 12.93 | 85.00 |
| - | 12.22 | 85.00 |
| | | |
| Other Crop | 0.00 | |
| Inert matter (Xalt seed coating product) | 50.56 | |
| Weed seed | 0.00 | |

[a] Vitality™, Maryland, USA

**Table 12.** 'EGS Tri' perennial ryegrass (*Lolium perenne* L.) blend seed label[a].

| Variety | Purity (%) | Germination (%) |
|---|---|---|
| Majesty | 33.22 | 90.00 |
| Spark | 33.17 | 90.00 |
| Salinas II | 31.59 | 90.00 |
| | | |
| Other Crop | 0.22 | |
| Inert matter | 1.80 | |
| Weed seed | 0.00 | |

[a] Landmark Seeds Inc., Oregon, USA.


**Figure 13**. Sod grown on plastic with varying seeding ratios: (**a**) harvested in July 2023 (nine months after establishment) at Carolina Green Sod Farm, North Carolina, USA, and (**b**) transported to Michigan State University in July 2023, East Lansing, Michigan, USA.

*FIFA Indoor Pitch Simulator Facility*

This study was conducted in the indoor testing facility, also known as the "FIFA Indoor Pitch Simulator", located at the University of Tennessee East Tennessee Research and Education Center, Knoxville, TN. The facility is an opaque, fully enclosed steel structure equipped with heating, ventilation, and air conditioning systems that maintain temperatures around 20-22°C, replicating an indoor stadium environment. It has twelve 2.7 m × 2.7 m bays, each equipped with its own irrigation system and light-emitting diode (LED) grow lights (SGL, NL). Each bay was exposed to 18 hours of artificial light daily, receiving a total of 22 mol $m^{-2}$ $d^{-1}$ (Figure 14).

*Assembling the shallow profile*

For each bay, 20 pieces of Permavoid 85s geocellular drainage (Permavoid, Amsterdam, NL) were placed directly on top of the concrete (Figure 15a). A Permatex 300 geotextile (Permavoid, Amsterdam, NL) was then laid over the geocellular drainage layer and secured with a wooden frame (Figure 15b). Then, sod grown on plastic was placed on top of the geotextile. In December 2023, a total of seventy-two 0.45 m × 0.45 m sod pieces (32 pieces per bay) were transferred inside the facility and were given four weeks to acclimate before the study began.

**Figure 14**. FIFA lighthouse illuminated with LED grow lights (Photo by J. Guevara).

.

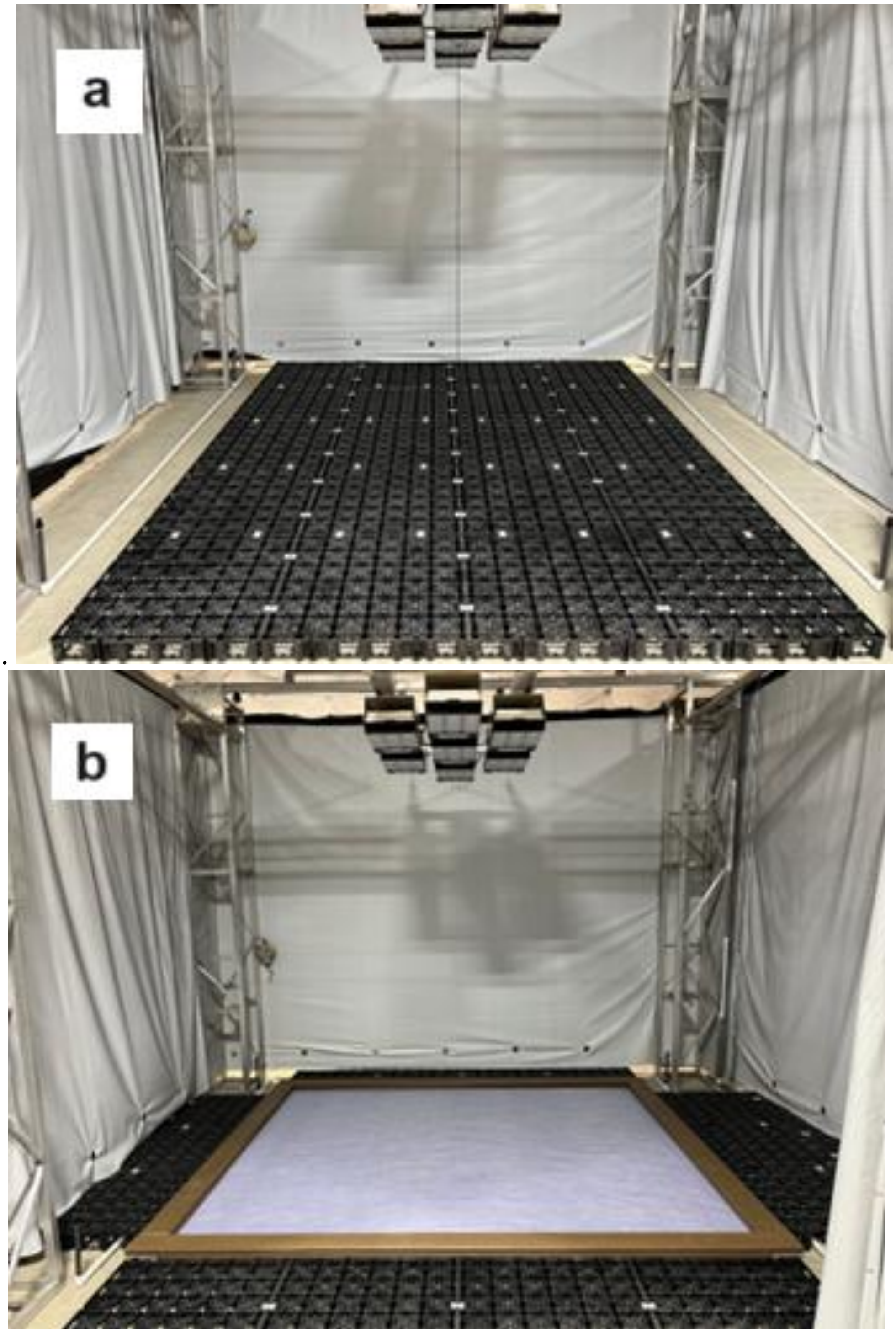


**Figure 15**. Components of the shallow profile inside the FIFA Lighthouse: **(a)** Permavoid 85s geocellular drainage; **(b)** Permatex 300 geotextile. (Photo by R. Fielder).

*Experimental design, treatment application and plot maintenance*

Due to delays in the construction of the FIFA Indoor Pitch Facility, the timeline for conducting this research was shortened. As a result, two runs of the study were conducted concurrently in two separate bays. To simulate the installation and maintenance for a domed stadium, the study began four weeks after installation (WAI) and lasted for five weeks, from January 22, 2024, to February 26, 2024. The study followed a two-factor split-plot randomized complete block design (Figure 16). The whole-plot factor included two levels of traffic treatment: trafficked and non-trafficked. Traffic was applied manually with 20 passes (10 passes back and forth) every week (Figure 17). The subplot factor included six levels of KBG and PRG seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16, and 0:100). Each subplot measured 0.45 m × 0.45 m. Plots were mown at 2.6 cm daily using an electric rotary mower. Fertilizers, fungicides and plant growth regulators were applied throughout the acclimation phase until the end of the study (Table 13).

**Table 13.** Fertilizer, fungicide and plant growth regulator application on the Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow profile plots inside the FIFA Indoor Pitch Simulator Facility – 2024.

| Week after installation | Date | Fertilizer | Fungicide | Plant growth regulator |
|---|---|---|---|---|
| 1 | 5-Jan | 1.2 g N $m^{-2}$ (46-0-0) | | |
| 2 | 11-Jan | 1.2 g N $m^{-2}$ (18-3-6) | 0.12 mL $m^{-2}$ HeritageAction [a] | |
| 3 | 18-Jan | | | 0.56 oz/M Primo Maxx [b] |
| 4 | 26-Jan | 1.2 g N / $m^{-2}$ (18-3-6) | 0.12 mL $m^{-2}$ Heritage Action | |
| 5 | 29-Jan | | | 0.56 oz/M Primo Maxx |
| 6 | 8-Feb | 1.2 g N / $m^{-2}$ (18-3-6) | 0.21 mL $m^{-2}$ Insignia SC [c] | |
| | 9-Feb | | 1.65 mL $m^{-2}$ DaconilAction [d] | 0.56 oz/M Primo Maxx |
| 8 | 22-Feb | 1.2 g N / $m^{-2}$ (18-3-6) | 0.21 oz/M Insignia SC | |

[a] 50% azoxystrobin; 1.18% acibenzolar-S-methyl (Syngenta ®, North Carolina, USA).
[b] 11.3% trinexapac-ethyl (Syngenta ®, North Carolina, USA), application followed a 200 GDD-interval (base temperature of 0°C).
[c] 23.3% pyraclostrobin (BASF, North Carolina, USA).
[d] 53.94% chlorothalonil (Syngenta ®, North Carolina, USA).

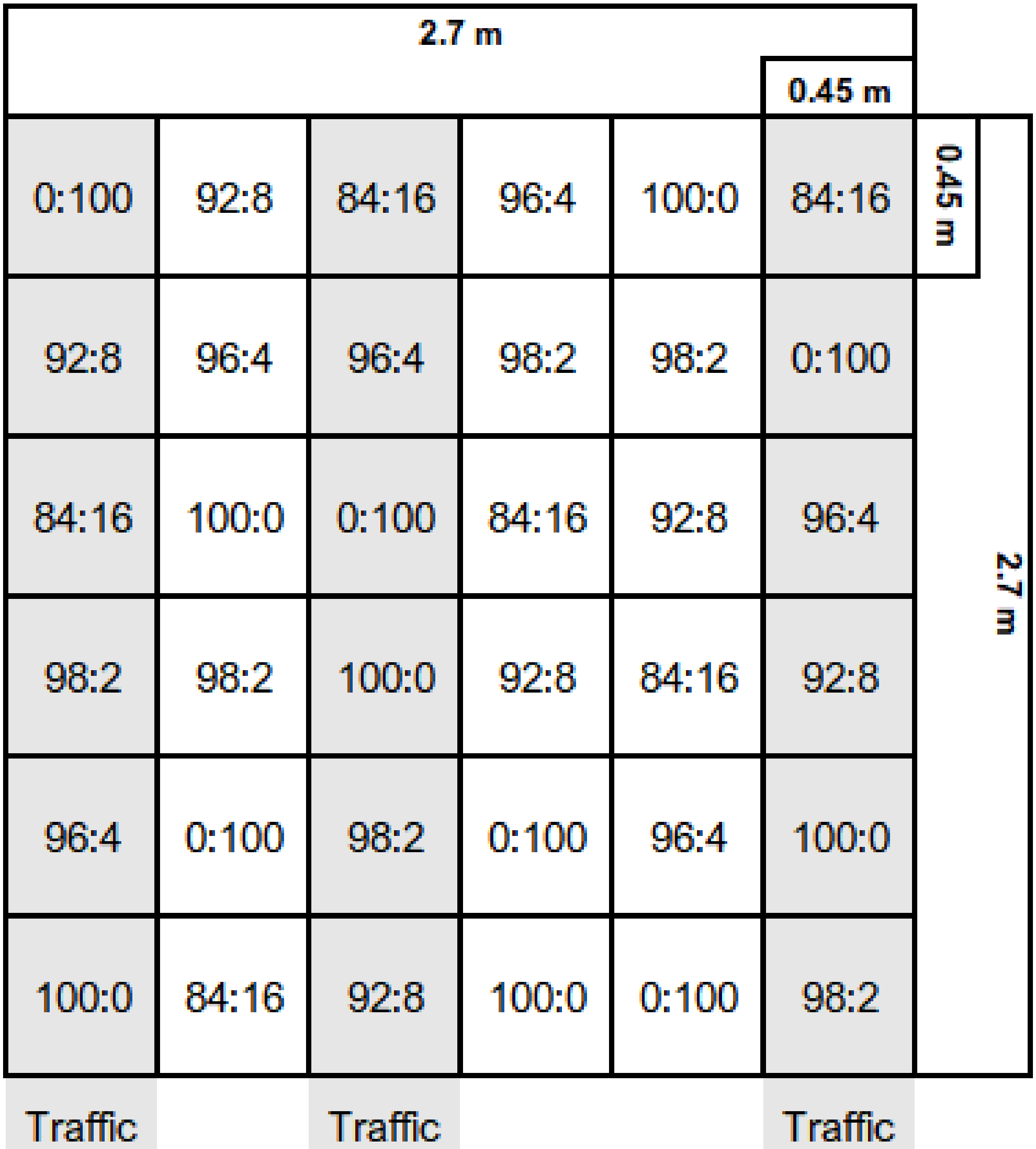


**Figure 16**. Experimental design and research plot map of each 2.7 m × 2.7 m bay. It illustrates the Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) seeding ratios (100:0, 98:2, 96:4, 92:8, 84:16 and 0:100) used to grow each 0.45 m × 0.45 m sod that was placed on top of the Permatex 300 geotextile and Permavoid 85s geocellular drainage.

**Figure 17.** Traffic application on the Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow profile plots inside the FIFA Indoor Pitch Simulator Facility at Knoxville, Tennessee, USA – 9 weeks after installation – February 19, 2024 (photo by J. Guevara).

*Data collection*

Turfgrass color, percent green cover and surface performance characteristics were measured – after traffic application – every week. Turfgrass color was quantified as normalized difference vegetation index (NDVI). It was measured using the average of three readings obtained with a FieldScout TCM 500 NDVI Turf Color Meter (Spectrum Technologies, USA). To quantify percent turfgrass cover, overhead images of each plot were captured using a Canon PowerShot SX730HS (Canon, USA) digital camera set to macro mode, ISO 800, F4.0, and 1/250s. To quantify percent turfgrass cover, a modified method based on Richardson et al. (2001) was used. Overhead images of each plot were captured using a Canon PowerShot SX730HS (Canon, USA) digital camera set to macro mode with the following settings: ISO 800, F4.0, and a shutter speed of 1/250s. The images were analyzed using ImageJ software. Surface performance characteristics such as maximum shear stress and maximum displacement were measured using the foot lower extremities (fLEX) machine (Dickson & Sorochan, 2022).

*Statistical analysis*

All data were analyzed using R software (R Core Team, 2024). Each bay were analyzed separately. Seeding ratio, traffic and measurement date, along with their interactions, were treated as fixed effects, whereas replication, traffic × replication and seeding ratio × traffic × replication were considered as random effects. The variance-covariance analysis structure with the lowest Akaike's Information Criterion and Bayesian information Criterion values was selected for further analyses. The analysis of variance (ANOVA) was conducted to examine the significance of fixed effects and their interactions. Post hoc mean separation tests were conducted using Fisher's Protected Least Significant Difference when F tests were significant at $\alpha$=0.05.

## Results and discussion

*Normalized Difference Vegetation Index*

No interaction between seeding ratio and traffic was observed in either bay across all measurement dates (Tables 14–15). Thus, the main effects of seeding ratio and traffic application were analyzed. Thus, the main effects of seeding ratio and traffic application were analyzed. The seeding ratio significantly influenced NDVI at 4, 5, and 9 WAI in Bay 1 (Table 14) and at 5, 8, and 9 WAI in Bay 2 (Table 15). Results near the end of the study showed variability. In Bay 1, pure PRG (0:100) exhibited the highest NDVI values, while pure KBG (100:0) had the lowest at 9 WAI (Table 14). In Bay 2, both pure KBG and PRG demonstrated the highest NDVI at 9 WAI (Table 15).

Traffic application had an effect on NDVI during the later stages of the study (Table 14). In Bay 1, significant differences were observed at 8 and 9 weeks after installation (WAI) (Table 14), while in Bay 2, the effects became evident at 7, 8, and 9 WAI (Table 15). Trafficked plots consistently exhibited lower NDVI compared to non-trafficked plots.

*Percent green cover*

No interaction between seeding ratio and traffic application was found across most measurement dates in either bay (Tables 16–17), with the exception of 9 WAI in Bay 2 (Table 17). A similar trend was observed for percent green cover. The seeding ratio significantly influenced percent green cover at 4 and 9 WAI in Bay 1 (Table 15) and at 8 WAI in Bay 2 (Table 16). In Bay 1, at 9 WAI, pure PRG exhibited the highest percent green cover, while pure KBG had the lowest. In Bay 2, at 8 WAI, both pure KBG and PRG had the highest percent green

Traffic application had a significant effect starting at 6 WAI. Trafficked plots displayed a lower percent green cover than non-trafficked plots (Tables 16–17). An interaction was observed in Bay 2, where trafficked plots generally showed lower percent green cover compared to non-trafficked plots (Table 16). However, in the pure PRG (0:100) plots, no significant difference was found between trafficked and non-trafficked conditions (Table 16). These findings align with expectations, as traffic was applied weekly. These highlight the detrimental effects of traffic application on turfgrass systems, particularly on shallow turfgrass profile, with noticeable result beginning as early as two traffic applications.

*Other influencing factors*

Several confounding factors were identified, as all seeding ratios exhibited a decline in NDVI and percent green cover over time (Tables 14–17). Disease was initially suspected; however, fungicides were consistently applied throughout the study to mitigate disease pressure. Another potential factor influencing the results was the application of a plant growth regulator (PGR) containing the active ingredient trinexapac-ethyl, a gibberellic acid inhibitor (Rademacher, 2000). Gibberellic acid inhibitors, such as flurprimidol, have been shown to mitigate the detrimental effects of shade (e.g., shoot elongation) and help maintain acceptable turfgrass quality under supplemental lighting (Stier, 1999).

The plant growth regulator applied at recommended following a 200 GDD model (base temperature of 0°C) (Kreuser, 2016). However, further investigation revealed that this recommendation was based on preliminary work with KBG and the established GDD interval for creeping bentgrass (*Agrostis stolonifera*) (Kreuser, 2015, 2016). Unlike KBG, creeping bentgrass requires a shorter reapplication interval of 1 to 3 weeks compared to the 4 to 6 weeks suggested for KBG (Stier & Rogers, 2001; McCullough et al., 2007). These findings shows that the application interval should be longer for KBG. These observations highlight an important consideration from this study – the interaction of chemical applications with shallow turfgrass profiles (2-inch root zones) compared to traditional 12-inch root zones. Differences in root zone depth may affect the efficacy of chemical treatments and present opportunities for further research.

**Table 14**. Analysis of variance testing for the effects of seeding ratios and traffic application on the normalized difference vegetation index of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 1 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Normalized Difference Vegetation Index [a] | | | | | |
|---|---|---|---|---|---|---|
| Effects | 4 WAI | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R)[b] | | | | | | |
| 100:0 | 0.80 a | 0.74 a | 0.73 | 0.57 | 0.54 | 0.58 c |
| 98:2 | 0.79 ab | 0.74 b | 0.71 | 0.60 | 0.54 | 0.61 bc |
| 96:4 | 0.77 c | 0.74 b | 0.71 | 0.59 | 0.54 | 0.60 bc |
| 92:8 | 0.78 ab | 0.73 b | 0.73 | 0.61 | 0.54 | 0.62 b |
| 84:16 | 0.79 a | 0.74 ab | 0.73 | 0.59 | 0.53 | 0.60 bc |
| 0:100 | 0.77 bc | 0.74 ab | 0.71 | 0.59 | 0.58 | 0.68 a |
| *p-value* | * | * | ns | ns | ns | *** |
| Traffic application (T) | | | | | | |
| Trafficked | 0.78 | 0.74 | 0.71 | 0.58 | 0.51 | 0.58 |
| Non-trafficked | 0.78 | 0.74 | 0.73 | 0.61 | 0.58 | 0.64 |
| *p-value* | ns | ns | ns | ns | * | * |
| R × T | ns | ns | ns | ns | ns | ns |

[a] measured using the average of three readings obtained with a FieldScout TCM 500 NDVI Turf Color Meter.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

**Table 15**. Analysis of variance testing for the effects of seeding ratios and traffic application on the normalized difference vegetation index of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 2 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Normalized Difference Vegetation Index [a] | | | | | |
|---|---|---|---|---|---|---|
| Effects | 4 WAI | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | | |
| 100:0 | 0.76 | 0.71 c | 0.68 | 0.56 | 0.58 b | 0.58 c |
| 98:2 | 0.77 | 0.76 a | 0.67 | 0.58 | 0.53 b | 0.61 bc |
| 96:4 | 0.76 | 0.73 ab | 0.69 | 0.57 | 0.52 b | 0.60 bc |
| 92:8 | 0.77 | 0.74 ab | 0.73 | 0.55 | 0.53 b | 0.62 b |
| 84:16 | 0.75 | 0.73 bc | 0.70 | 0.58 | 0.53 a | 0.60 bc |
| 0:100 | 0.74 | 0.72 bc | 0.69 | 0.57 | 0.60 a | 0.68 a |
| *p-value* | ns | * | ns | ns | *** | *** |
| Traffic application (T) | | | | | | |
| Trafficked | 0.76 | 0.72 | 0.69 | 0.54 | 0.51 | 0.60 |
| Non-trafficked | 0.75 | 0.73 | 0.71 | 0.60 | 0.59 | 0.67 |
| *p-value* | ns | ns | ns | * | * | * |
| R × T | ns | ns | ns | ns | ns | ns |

[a] measured using the average of three readings obtained with a FieldScout TCM 500 NDVI Turf Color Meter.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

**Table 16**. Analysis of variance testing for the effects of seeding ratios and traffic application on the percent green cover Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 1 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Percent green cover [a] | | | | | |
|---|---|---|---|---|---|---|
| Effects | 4 WAI | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | | |
| 100:0 | 94 a | 91 | 91 | 74 | 70 | 70 b |
| 98:2 | 94 a | 90 | 90 | 76 | 71 | 75 b |
| 96:4 | 90 b | 86 | 86 | 73 | 69 | 72 b |
| 92:8 | 94 a | 89 | 89 | 76 | 73 | 75 b |
| 84:16 | 95 a | 88 | 88 | 73 | 72 | 74 b |
| 0:100 | 94 a | 88 | 87 | 73 | 75 | 84 a |
| *p-value* | * | ns | ns | ns | ns | *** |
| Traffic application (T) | | | | | | |
| Trafficked | 94 | 88 | 77 | 69 | 65 | 67 |
| Non-trafficked | 93 | 89 | 84 | 79 | 78 | 82 |
| *p-value* | ns | ns | * | * | * | * |
| R × T | ns | ns | ns | ns | ns | ns |

[a] overhead digital images were analyzed using ImageJ.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

**Table 17**. Analysis of variance testing for the effects of seeding ratios and traffic application on the percent green cover of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 2 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Percent green cover [a] | | | | | |
|---|---|---|---|---|---|---|
| Effects | 4 WAI | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | | |
| 100:0 | 92 | 83 | 71 | 66 | 73 a | 83 |
| 98:2 | 93 | 87 | 79 | 68 | 61 b | 66 |
| 96:4 | 92 | 86 | 78 | 68 | 62 b | 67 |
| 92:8 | 93 | 85 | 76 | 65 | 62 b | 67 |
| 84:16 | 93 | 87 | 79 | 69 | 65 b | 69 |
| 0:100 | 93 | 85 | 76 | 68 | 75 a | 87 |
| *p-value* | ns | ns | ns | ns | *** | *** |
| Traffic application (T) | | | | | | |
| Trafficked | 93 | 84 | 70 | 56 | 56 | 64 |
| Non-trafficked | 92 | 87 | 82 | 78 | 77 | 82 |
| *p-value* | ns | ns | * | * | * | * |
| R × T | ns | ns | ns | ns | ns | * |

[a] overhead digital images were analyzed using ImageJ.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.
*, significant at $p < 0.05$.
**, significant at $p < 0.01$.
***, significant at $p < 0.001$.

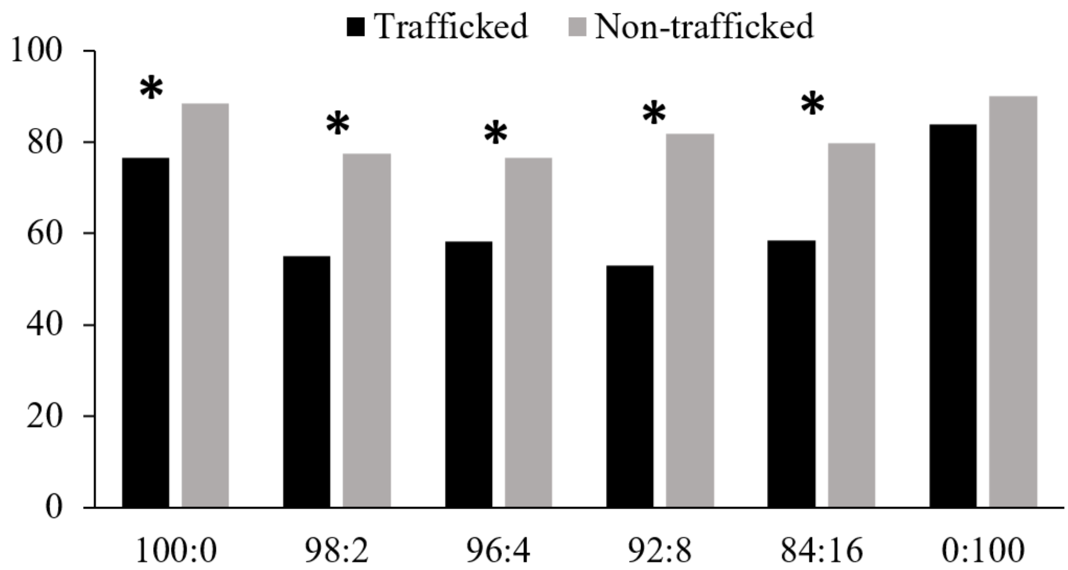


**Figure 18.** Interaction of seeding ratio and traffic application on Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow profile plots inside the FIFA Indoor Pitch Simulator Facility, Knoxville, Tennessee, USA, on February 19, 2024 (9 weeks after installation). * indicates significant differences within seeding ratio treatments.

*Playing surface performance characteristics*

Maximum shear strength refers to the highest resistance a material exhibits before failure. There was no interaction or significant difference observed between seeding ratios and traffic application, with all seeding ratio treatments performing similarly. Maximum displacement refers to the maximum distance a surface deforms when subjected to a force, often described as the "give" of the surface. Similar to maximum shear strength, no interaction or significant difference was observed between seeding ratios and traffic application. Although the results were not statistically significant, the values were compared to the target range for the fLEX beta prototype, which is 60 to 75 mm (Sorochan & Dickson, personal communication). The observed values exceeded this range, potentially due to organic matter accumulation, which may have contributed to increased displacement. These findings indicate that the playing surface performance characteristics were not significantly affected by either seeding ratio or traffic application.

**Table 18**. Analysis of variance testing for the effects of seeding ratios and traffic application on the maximum shear stress of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 1 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Maximum shear stress (N) [a] | | | | |
|---|---|---|---|---|---|
| Effects | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | |
| 100:0 | 2105 | 2089 | 1591 | 1877 | 1733 |
| 98:2 | 1965 | 1969 | 1513 | 1874 | 1724 |
| 96:4 | 2129 | 2097 | 1511 | 1879 | 1744 |
| 92:8 | 1910 | 2112 | 1536 | 1850 | 1702 |
| 84:16 | 2280 | 2050 | 1415 | 1855 | 1685 |
| 0:100 | 1899 | 2103 | 1621 | 1853 | 1711 |
| *p-value* | ns | ns | ns | ns | ns |
| Traffic application (T) | | | | | |
| Trafficked | 2131 | 2098 | 1538 | 1870 | 1715 |
| Non-trafficked | 1965 | 2042 | 1523 | 1859 | 1718 |
| *p-value* | ns | ns | ns | ns | ns |
| R × T | ns | ns | ns | ns | ns |

[a] measured using the foot lower extremities (fLEX) machine.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.

**Table 19**. Analysis of variance testing for the effects of seeding ratios and traffic application on the maximum shear stress of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 2 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Maximum shear stress (N) [a] | | | | |
|---|---|---|---|---|---|
| Effects | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | |
| 100:0 | 2115 | 1769 | 1351 | 1828 | 1707 |
| 98:2 | 2089 | 1740 | 1348 | 1825 | 1721 |
| 96:4 | 1956 | 1952 | 1526 | 1833 | 1725 |
| 92:8 | 2061 | 1979 | 1508 | 1849 | 1716 |
| 84:16 | 2093 | 2154 | 1628 | 1830 | 1721 |
| 0:100 | 2047 | 2053 | 1478 | 1815 | 1693 |
| *p-value* | ns | ns | ns | ns | ns |
| Traffic application (T) | | | | | |
| Trafficked | 2148 | 1977 | 1465 | 1819 | 1718 |
| Non-trafficked | 1972 | 1905 | 1481 | 1841 | 1710 |
| *p-value* | ns | ns | ns | ns | ns |
| R × T | ns | ns | ns | ns | ns |

[a] measured using the foot lower extremities (fLEX) machine.
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.

**Table 20**. Analysis of variance testing for the effects of seeding ratios and traffic application on the maximum displacement of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 1 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Maximum displacement (mm) [a] | | | | |
|---|---|---|---|---|---|
| Effects | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) [b] | | | | | |
| 100:0 | 77.9 | 78.3 | 68.1 | 74.5 | 75.2 |
| 98:2 | 79.5 | 72.6 | 66.6 | 75.5 | 79.4 |
| 96:4 | 76.0 | 78.5 | 67.4 | 74.1 | 76.8 |
| 92:8 | 65.1 | 78.6 | 70.6 | 80.1 | 81.8 |
| 84:16 | 87.9 | 72.2 | 64.5 | 82.4 | 81.3 |
| 0:100 | 79.7 | 76.6 | 68.5 | 73.3 | 74.9 |
| *p-value* | ns | ns | ns | ns | ns |
| Traffic application (T) | | | | | |
| Trafficked | 72.8 | 75.7 | 66.3 | 75.5 | 78.2 |
| Non-trafficked | 82.5 | 76.6 | 68.9 | 77.8 | 78.3 |
| *p-value* | ns | ns | ns | ns | ns |
| R × T | ns | ns | ns | ns | ns |

[a] measured using the foot lower extremities (fLEX) machine. Green cells indicate values within the safe range, while red cells represent values outside the acceptable range, as determined using the Foot Lower Extremities (fLEX) machine (Sorochan and Dickson, personal communication).
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.

**Table 21**. Analysis of variance testing for the effects of seeding ratios and traffic application on the maximum displacement of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) shallow turfgrass profile system, evaluated on Bay 2 at the FIFA Indoor Pitch Simulator Facility, Tennessee, USA — 2024.

| | Maximum displacement (mm) [a] | | | | |
|---|---|---|---|---|---|
| Effects | 5 WAI | 6 WAI | 7 WAI | 8 WAI | 9 WAI |
| Seeding ratio (R) b | | | | | |
| 100:0 | 79.6 | 76.2 | 65.9 | 77.8 | 79.3 |
| 98:2 | 83.2 | 78.6 | 72.6 | 81.4 | 83.4 |
| 96:4 | 79.8 | 81.4 | 71.2 | 82.9 | 78.5 |
| 92:8 | 79.7 | 79.9 | 70.0 | 77.8 | 78.1 |
| 84:16 | 79.6 | 82.9 | 72.5 | 77.4 | 77.6 |
| 0:100 | 84.7 | 80.5 | 69.6 | 77.0 | 78.5 |
| *p-value* | ns | ns | ns | ns | ns |
| Traffic application (T) | | | | | |
| Trafficked | 83.3 | 79.0 | 68.5 | 78.2 | 79.3 |
| Non-trafficked | 78.8 | 80.9 | 71.8 | 79.9 | 79.2 |
| *p-value* | ns | ns | ns | ns | ns |
| R × T | ns | ns | ns | ns | ns |

[a] measured using the foot lower extremities (fLEX) machine. Green cells indicate values within the safe range, while red cells represent values outside the acceptable range, as determined using the Foot Lower Extremities (fLEX) machine (Sorochan and Dickson, personal communication).
[b] Kentucky bluegrass: perennial ryegrass seeding ratio.
WAI, weeks after installation.
ns, not significant at $p \geq 0.05$.

## Conclusions

All KBG:PRG seeding ratios demonstrated similar results in turfgrass color, percent green cover, maximum shear strength, and maximum displacement, indicating that any of the tested ratios would perform similarly within a stadium setting. As anticipated, traffic application significantly reduced turfgrass color and percent green cover, with noticeable effects occurring as early as two traffic events. Several factors likely influenced these outcomes, raising additional questions for future research such as the potential effects of root zone depth on the efficacy of chemical applications, including fertilizers, fungicides, and plant growth regulators. Determining appropriate application intervals for plant growth regulators, especially within shallow turfgrass profile systems, is another area for further investigation. Additionally, the effects of artificial lighting systems on turfgrass growth and quality should continue to be explored to optimize management practices for indoor controlled environments.

## REFERENCES


Abélard, E., & Galbrun, C. (2022). The effects of artificial lighting on sports turf. *International Turfgrass Society Research Journal*, *14*(1), 1016–1021. https://doi.org/10.1002/its2.115

Christians, N. E., Patton, A. J., & Law, Q. D. (2016). *Fundamentals of Turfgrass Management, Fifth Edition* (1st ed.). Wiley. https://doi.org/10.1002/9781119308867

Decker, H. (2001). Producing Sods over Plastic in Soilless Media. In J. Janick (Ed.), *Horticultural Reviews* (1st ed., Vol. 27, pp. 317–351). Wiley. https://doi.org/10.1002/9780470650813.ch8

Dickson, K., & Sorochan, J. (2022). *New Device to Test Uniformity and Consistency of Athletic Fields [Abstract]*. ASA, CSSA, SSSA International Annual Meeting. Baltimore, MD. https://scisoc.confex.com/scisoc/2022am/meetingapp.cgi/Paper/143526

Dudeck, A., & Peacock, C. (1992). Shade and Turfgrass Culture. In D. Waddington, R. Carrow, & R. Shearman (Eds.), *Agronomy Monographs* (pp. 269–284). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr32.c8

Fédération Internationale de Football Association. (2022). *FIFA World Cup 2022 Qatar Regulations*. Fédération Internationale de Football Association. https://digitalhub.fifa.com/m/2744a0a5e3ded185/original/FIFA-World-Cup-Qatar-2022-Regulations_EN.pdf

Gould, H., Lostetter, S., Samuelson, E. R., & Guyton, G. P. (2022). Lower Extremity Injury Rates on Artificial Turf Versus Natural Grass Playing Surfaces: A Systematic Review. *The American Journal of Sports Medicine*, *51*(6), 1615–1621. https://doi.org/10.1177/03635465211069562

Guevara, J., Bearss, R., Kilby, J., Rogers, E., Rogers, J., Fielder, R., Burbrink, C., Navarette, I., Williams, T., Dickson, K., & Sorochan, J. (2024, July 8). Assessing drainage mats for shallow profile football pitch. *ISEA 2024: The Engineering of Sport 15*.

Kreuser, B. (2015). Effective use of plant growth regulators on golf putting greens: To maximize the potential of plant growth regulators, growing degree-day models offer a simple and effective way to estimate PGR performance. *USGA Green Section Record*, *53*(7), 1–10.

Kreuser, B. (2016). GDDs for Timing PGR Applications: Impact on Growth & Performance. Lincoln, Nebraska: *University of Nebraska-Lincoln*. 112 slides.

Lehnert, R. (1993). Laying the groundwork for World Cup Soccer. *SportsTURF*, *9*(6), 8,11-13.

Li, D., Henderson, J., Tim Vanini, J., & Rogers, J. (2015). Research Tools and Technologies for Turfgrass Establishment. In J. Stier, B. Horgan, & S. Bonos (Eds.), *Turfgrass: Biology, Use, and Management* (pp. 1189–1239). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr56.c31

McCullough, P., Liu, H., McCarty, L., & Toler, J. (2007). Trinexapac-ethyl applicaiton regimens influence growth, quality, and performance of bermuda grass and creeping bentgrass putting greens. *Crop Science.*, *47*(5), 2138–2144.

McInnes, K. J., & Thomas, J. C. (2011). Water Storage in Putting Greens Constructed with United States Golf Association and Airfield Systems Designs. *Crop Science*, *51*(3), 1261–1267. https://doi.org/10.2135/cropsci2010.08.0498

Neel, P., Burt, E., Busey, P., & Snyder, G. (1978). Sod Production in Shallow Beds of Waste Materials1. *Journal of the American Society for Horticultural Science*, *103*(4), 549–553. https://doi.org/10.21273/JASHS.103.4.549

Odgaard, N. (2003). Seahawks Stadium: A natural for soccer match. *SportsTURF*, *19*(5), 24–25.

R Core Team. (2024). *R: A language and environment for statistical computing. R Foundation for Statistical Computing* [Computer software]. https://www.R-project.org/

Rademacher, W. (2000). Growth retardants: effects on gibberellin biosynthesis and other metabolic pathways. *Annual Review of. Plant Biology*, *51*, 501–531.

Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying Turfgrass Cover Using Digital Image Analysis. *Crop Science*, *41*(6), 1884–1888. https://doi.org/10.2135/cropsci2001.1884

Ripley, T., & Indyk, H. (1993). *Turfing systems for Stadia* (US Patent 5 187 894).

Rogers, J., Stier, J., & Crum, J. (1993). Indoor turf/World Cup ’94 soccer tournament project update. *TurfNews [ASPA]*, *17*(6), 18–19.

Rogers, J., Stier, J., Crum, J., & Rieke, P. (1995). Indoor turf/ World Cup ’94 project update. *Proceedings of the 65th Annual Michigan Turfgrass Conference*, *24*, 227–229.

Rogers, J., Stier, J., Crum, J., Rieke, P., & Lawson, T. (1994). Facts sheet for natural turfgrass pitch at Pontiac Silverdome for US Cup ’93/World Cup ’94. *Proceedings of International Symposium on Soccer Field*, 89-91,167-170.

Rose-Harvey, K., McInnes, K. J., & Thomas, J. C. (2012). Water Flow Through Sand-based Root Zones Atop Geotextiles. *HortScience*, *47*(10), 1543–1547. https://doi.org/10.21273/HORTSCI.47.10.1543

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

SportsTURF. (1997). Giants Stadium tests a new field-on-wheels. *SportsTURF*, 18-20,22.

Stier, J., & Rogers, J. (2001). Trinexapac-Ethyl and Iron Effects on Supina and Kentucky Bluegrasses Under Low Irradiance. *Crop Science*, *41*(2), 457–465.

Stier, J., Rogers, J., Crum, J., & Rieke, P. (1999). Flurprimidol effects on Kentucky bluegrass under reduced irradiance. *Crop Science*, *39*(5), 1423–1430.

Tretter, J. (2024). *Only Natural Grass Can Level The NFL's Playing Field | NFLPA*. https://nflpa.com/posts/only-natural-grass-can-level-the-nfls-playing-field

Young, T., Mann, R., & Spring, C. (2022). Use of plastic geocellular modules as a replacement gravel layer for natural turf rootzones. *International Turfgrass Society Research Journal*, *14*(1), 339–351. https://doi.org/10.1002/its2.99