IMPACT OF NATURAL TURFGRASS SPORTS FIELD CHARACTERISTICS AND MANAGEMENT STRATEGIES ON FIELD QUALITY AND PLAYABILITY

A Thesis

by

OPEYEMI EMMANUEL ALABI

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Chase Straw
Co-Chair of Committee,	Chrissie Segars
Committee Members,	Benjamin Wherley
	Athol Thomson
	Steven Riechman
Head of Department,	David Baltensperger

August 2023

Major Subject: Agronomy

ABSTRACT

Growing budget and labor constraints are becoming a burden for facilities in the construction and management of natural turfgrass sports fields, so there is interest in economical alternative options to meet demand while still providing quality playing surfaces. The overarching objective of this research was to evaluate the impact of several turfgrass sports field characteristics and management strategies on field quality and playability. Specifically, three studies were conducted that evaluated the 1) influence of plant growth regulator application strategies (rate, reapplication interval, and stoppage) and cultivation practices (raking and verticutting) on overseeded hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt Davy] sports field surface characteristics during simulated American football seasons, 2) traffic tolerance and recovery of several commercially available and experimental zoysiagrass cultivars compared to an industry standard hybrid bermudagrass cultivar under two traffic levels (moderate and high), and 3) effect of turfgrass species [i.e., bermudagrass, bermudagrass overseeded with perennial ryegrass (*Lolium perenne* L.), and seashore paspalum (*Paspalum vaginatum*)], soil moisture (“wet” and “dry”), and mowing height (“high” and “low”) on soccer athletes’ peak tibial accelerations during athletic maneuvers. Results from the first study showed that raking treatment effectively managed density with minimal impact on turfgrass quality, and stopping split rate PGR application before the season yielded comparable results to continuous full-rate application. In the second study, one of the zoysiagrass experimental varieties (‘DALZ 1818’) showed promise in terms of visual quality and energy restitution, but had the least desirable surface characteristics. Lastly, athletes’ biomechanics and perception, as well as field performance testing data indicated that dry-low management zone was preferred and had the highest peak tibial acceleration. Findings from this

research provide sports field managers with additional options for constructing and maintaining their turfgrass sports fields to maximize field quality, playability, and safety.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the chair and co-chair of my committee, Drs. Chase Straw and Chrissie Segars, as well as members of my committee Drs. Benjamin Wherley, Athol Thomson, and Steven Riechman for their immense contribution towards the successful completion of my research.

I would like to also extend this gratitude to Mr. Weston Floyd, Mr. Bruce Vento, fellow graduate students, and the student workers at the Texas A&M University Turfgrass Field Laboratory for their support that ensured the smooth running of my research.

Finally, I would like to thank my family for their support and encouragement during this time.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professors Straw [Chair] and Wherley of the Department of Soil and Crop Sciences, Professor Riechman of the Department of Kinesiology, Dr. Segars [Co-Chair] of PBI-Gordon Corporation, and Dr. Thomson of Aspetar Orthopaedic and Sports Medicine Hospital.

Assistance with a portion of the data analysis for Chapter 2 was provided by Professor Shawn Seung-Yeon of the Department of Statistics. Mr. Conlan Burbrink also helped with data handling and cleaning of the inertial measurement units in Chapter 4.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

This research was supported by grants from Texas Turfgrass Research Extension and Education Endowment (TTREEE) and Sports Field Management Association (SFMA).

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

CHAPTER I

REVIEW OF LITERATURE

1.1. Warm-season turfgrass sports fields

Warm-season turfgrass species are widely used on southern United States sports fields. They are perennial C_4 plants that photosynthesize by reacting CO_2 with the 3-carbon compound phosphoenolpyruvate (PEP) in the mesophyll cells to produce the 4-carbon compound oxaloacetate (OAA). Malate (4-carbon) is converted from OAA and moved to the bundle sheath cells, where carbon fixation occurs and carbohydrate is produced for plant use [1]. This process of carbon fixation is catalyzed by the enzyme PEP carboxylase, and is more efficient than cool-season turfgrasses (C_3 plants) by allowing the continuation of energy production for growth even when the stomata are closed. As a result, warm-season turfgrasses exhibit high water use efficiency, thereby making them the better option in hot and dry environments [2].

A few of the most common species used on sports fields include hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt Davy], zoysiagrass (*Zoysia spp.*), and seashore paspalum (*Paspalum vaginatum*). Generally, all of these species are wear tolerant, exhibit dense growth, and can be mowed at low heights, making them suitable for sports fields. However, each species has its own distinct characteristics that may render it more suitable in certain scenarios.

Hybrid bermudagrasses are genetic crosses of common bermudagrass [*C. dactylon* (L.) Pers] and African bermudagrass (*C. transvaalensis* Burtt-Davy) [3]. Common bermudagrass is tall-growing, light green colored, coarse-textured, and cold-sensitive with varying levels of drought tolerance. African bermudagrass is low-growing, dark green colored, fine-textured, and drought and cold-tolerant [3, 4]. Combinations of these desirable traits make hybrid bermudagrasses the most preferred warm-season turfgrass for sports fields because of their fine-textured leaf blades and dense cover [5], in addition to their excellent traffic tolerance and recovery. Common bermudagrasses are prone to risk of producing off types and causing discoloration, whereas these interspecific hybrid bermudagrass cultivars are sterile and such risk is limited. As a result of the sterile nature of hybrid bermudagrass cultivars, they are established only from sprigs or sod. Popular hybrid bermudagrass cultivars commercially produced today include: ‘TifTuf,’ ‘Latitude 36,’ ‘Tahoma 31,’ and ‘IronCutter.’

Zoysiagrass and seashore paspalum are used much less on sports fields than bermudagrasses. Zoysiagrass varieties include *Z. japonica* (coarse textured leaf) and *Z. matrella* (fine textured leaf). They both have excellent turfgrass quality, are wear and shade tolerant, and require less maintenance inputs (e.g., water, fertilizer) than other warm-season turfgrasses [6-11]. *Z. japonica* is common in the transition zone of the United States because of its cold and wear tolerance, whereas *Z. matrella* generally exhibits the greater turfgrass quality and shade, salinity, and low mowing tolerance [10, 12-14]. Some studies have shown that *Z. matrella* genotypes are able to maintain approximately 50 to 75% ground cover in 90% shade without traffic [14, 15]. Despite the wear tolerance of zoysiagrasses (*Z. japonica* specifically), slow recovery is their primary weakness and makes them not suitable for use on heavily trafficked sports fields. Nonetheless, they can perform well on stadium fields with limited or minimal traffic [16, 17]. Some popular commercially available cultivars of zoysiagrass today include ‘Meyer,’ ‘Zeon,’ and ‘Zorro.’

Seashore paspalum is of interest on sports fields due to its lower management input requirements and salinity tolerance, where it can survive in soils with pH ranging from 3.6 to 10.2 [18, 19]. Since it is the most salt tolerant turfgrass species [19], the halophytic nature of seashore paspalum allows it to endure up to oceanic salt concentration levels (54 dSm^{-1}) and makes it very suitable for regions with poor quality irrigation water [20, 21]. Seashore paspalum's cold tolerance is limited, and it becomes dormant when temperatures drop below 10-13 °C [22, 23]. Moreover, the shade tolerance level of seashore paspalum is higher than bermudagrass, as reported in a study where all the paspalum entries (‘Sea Isle 1,’ Cloister,’ ‘Sea Isle 2000,’ ‘Salam,’ ‘Q 36313,’ ‘561-79,’ and ‘Hybrid 5’) performed better under 70 and 90% shade than the bermudagrass entries (‘TifSport’ and ‘TifEagle’) [24]. Hence, there is an increasing use of seashore paspalum in soccer stadiums, and popular cultivars of include ‘Platinum TE,’ ‘SeaStar,’ ‘SeaIsle 1,’ and ‘AquaLawn.’

1.2. Soil types for turfgrass sports fields

Sports fields are typically constructed on either native or sand-based soil rootzones. Native soils vary by region and will generally contain a proportion of silt and clays, except along the coast where native soils are sandier. Because of the higher silt and clay content, native soils hold more water and are susceptible to soil compaction [25]. The higher water holding capacity of native soils is due to the small sized silt and clay particles with larger surface area and pore space relative to their volume that can hold onto water through surface tension and other adhesive forces [1]. These small-sized particles can also increase the susceptibility of soil compaction because they fill up the macropores and hinder permeability and water infiltration. Nevertheless, with adequate soil moisture they can offer excellent surface stability for sports fields, but field performance and safety can deteriorate during times of drought (e.g., they become too hard) and after intense rainfalls (e.g., they become too soft) [26, 27].

Sand-based soils contain nearly 100% sand that allows a significantly higher rate of water infiltration compared to native soils [25]. These rootzones retain structure and increased water infiltration rates during periods of intense foot traffic and heavy rainfall. There are two primary sand-based rootzone construction types for sports fields: the United States Golf Association (USGA) specification and sand-capping. A USGA specification sand rootzone is constructed to a depth of 30 cm and recommended to contain 50-80% of soil particles ranging from 0.25 to 2 mm in diameter, angular or sub-angular shape, less than 3% organic matter weight, 1.4 to 1.6 g cm^{-3} bulk density, 35 to 55% porosity, and ≥ 150 mm hr^{-1}saturated hydraulic conductivity to ensure good growing conditions, proper drainage, and soil stability [26, 28]. Another growing construction/renovation procedure for sports fields is sand-capping, which is the process of applying a layer of coarse sand with compatible size, shape, and composition over the existing soil profile [29]. Both types of aforementioned root zones can alleviate problems of soil compaction, promote healthy turfgrass growth, and improve field playability through soil moisture management and soil stability. However, USGA specification sand rootzone is very expensive to construct. Even though sand-capping is less expensive, it is sometimes developed without inclusion of subsurface drainage, can cause accumulation of excess water at the sand/soil interface. Further, if the wrong capping depth is used, the turfgrass performance and playing surface can be negatively affected [28, 30].

1.3. Traffic tolerance

Turfgrass sports fields are exposed to abiotic stress in the form of foot traffic from use, which can result in wear and soil compaction [5]. Wear refers to the damage inflicted on turfgrass due to scuffing, pressure, or tearing of the turfgrass tissue, while soil compaction refers to the compression of soil particles, which leads to an increase in soil density and a reduction in pore space [31]. Wear injury affects the shoot by stripping away leaf tissue, causing chlorophyll degradation and a decrease in photosynthesis [5]. Warm-season turfgrasses are generally more resistant to wear than cool-season turfgrasses [16], and the factors that will increase wear tolerance vary among and within species [16, 32]. Therefore, turfgrass varieties that are selected for heavily trafficked fields are chosen based on their capacity to withstand traffic or their ability to recover quickly from injury [5]. Recovery rates also depend on the inherent growth rate of the turfgrass species and the severity of the injury [33].

Foot traffic simulation devices to mimic sports field traffic for research were introduced in the 1940’s [34]. The early machines were designed to replicate traffic stress by applying both shearing and compaction forces using rubber-wheels, rollers, and studded drums. While these designs were durable and caused considerable injury to the turfgrass, they failed to replicate the forces of different magnitudes and directions typically experienced on sports fields. Traffic simulators today are improved and derive from modified aerification units, such as the Cady traffic simulator (CTS) and Baldree traffic simulator (BTS). The major difference between the CTS and BTS is the distribution of the force they produce. CTS applies only vertical force to the turfgrass, while BTS applies both vertical and horizontal forces, which is more like foot traffic observed in real-world sport fields situations.

In a study conducted by Deaton and Williams [35] that used the BTS, it was reported that the main effect of cultivar was significant in traffic tolerance. The cultivars used in the study were a mixture of common and hybrid bermudagrasses and consisted of ‘Quickstand,’ ‘Tifway’ ‘Riviera,’ and ‘Yukon’ established on a sand-based medium. Riviera and Tifway were more tolerant to simulated traffic in the study than Quickstand and Yukon in both years. A different study by Thoms et al. [36] using a CTS, investigated the impact of overseeding with perennial ryegrass (*Lolium perenne* L.) on traffic tolerance in bermudagrass and found that overseeding helped protect the bermudagrass from traffic damage during the fall season, thereby minimizing the effects of wear. Furthermore, when the wear tolerance of seven seashore paspalum (*Paspalum vaginatum* Swartz.) ecotypes (four fine-textured: ‘Temple 1,’ ‘HI-1,’ ‘SIPV-2,’ and ‘K1,’ three medium-coarse-textured: ‘AP 8,’ ‘PI 509022,’ and the cultivar ‘Adalayd’) was compared to that of hybrid bermudagrass (Tifway, ‘TifSport,’ and ‘TifGreen’), the results showed that higher tissue rigidity, a dense turfgrass canopy, and sufficient stem moisture were key factors that contributed to improved wear tolerance in bermudagrass [5].

1.4. Sports field management practices

The goal of every sports field manager should be to maintain a safe, playable, healthy, and aesthetically pleasing surface. To achieve this goal and combat foot traffic, proper fundamental turfgrass management practices should be employed with regards to irrigation, fertilization, mowing, and pest management. These practices will differ depending on turfgrass species and soil type, as well as the level of competition being played and expectations of the field. In general, native soil fields will require less irrigation and fertilization than sand-based fields because of the presence of fine-textured soil (clay) with a higher water holding capacity and cation exchange capacity [37].

Mowing height and frequency is influenced by available labor and equipment. Plant growth regulators (PGRs) can be beneficial to decrease vertical growth and reduce mowing frequency [38]. Plant growth regulators are broadly classified into two categories: Type I that inhibits cell division and Type II that interferes with the biosynthesis of gibberellin. Generally, Type I PGRs are used cautiously because of possible phytotoxicity and root injury, hence they are mostly used as herbicides to suppress seed head production in a common turfgrass weed, annual bluegrass (*Poa annua*). The most used Type II PGRs are Class A and B [39]. Class A PGRs inhibit gibberellin synthesis late in the biosynthesis pathway and are absorbed through the leaves and crowns of the turfgrass (e.g., trinexapac-ethyl; TE). Class B PGRs inhibit gibberellin synthesis early in the biosynthesis pathway and are generally absorbed through the roots (e.g., flurprimidol and paclobutrazol).

Trinexapac-ethyl is the most used PGR by sport field managers to inhibit vertical shoot growth, shorten internode lengths for denser canopy, and promote lateral growth of the turfgrass. Brosnan et al. [40] conducted one of few studies investigating benefits of TE under simulated traffic. They found TE alone and in combination with other PGRs (paclobutrazol, flurprimidol, and ethephon) resulted in improvements of color, quality, and cover of ‘Riviera’ bermudagrass when applied before traffic stress [40]. In a separate study by McCarty et al. [41], the application of TE resulted in excellent turfgrass quality, decreased vertical shoot growth, and did not impede lateral growth in Tifway bermudagrass. Other benefits of TE include enhanced turfgrass rooting, total nonstructural carbohydrate levels, cell density, and chlorophyll concentration in turfgrass leaves [41-43]. It is hypothesized that these benefits may contribute to increased turfgrass traffic tolerance, but there has been limited research on newer varieties of bermudagrass under simulated trafficked scenarios.

Cultivation practices like vertical mowing (i.e., verticutting), raking, and aerification are important for thatch and soil compaction management of warm-season turfgrass sports fields. The aggressive growth habits of warm-season turfgrasses can be beneficial for recovery from foot traffic and improving playability characteristics of a surface [44], yet excessive growth poses the risk of becoming soft [45]. Rapid thatch accumulation combined with high soil compaction also reduces hydraulic conductivity and promotes anaerobic conditions that cause a decline in field quality by making the turfgrass more susceptible to pests [46].

Verticutting is the use of a gasoline-powered or PTO-driven vertical mower fixed with vertically oriented blades that goes into the surface at varying depths, usually about 0.3 to 1.3 cm, to remove some of the thatch layer. This is an effective, although aggressive, method of dethatching; therefore, aesthetics can be negatively affected until the turfgrass has recovered. A less aggressive dethatching method is a spring-tined rake. Rakes are tow-behind and work by dragging the tines across the surface to dethatch and stand-up stolons that can be mowed and caught with mower buckets later.

Aerification is the process of creating small holes in the soil of sports fields to alleviate soil compaction, promote gas exchange, and improve water infiltration and microbial activity on heavily trafficked sports fields. The holes can be created using different tines like hollow and solid that remove cores or simply poke a hole in the surface, respectively. Solid tines can be used for aerification during season without disrupting scheduled play. The depth and spacing used can vary and will influence the effectiveness and recovery of the field. Finally, topdressing is the process of applying a thin (usually less than 6 mm) layer of sand to the surface to improve the overall health of the turfgrass by smoothing out the surface and enhancing soil structure, water infiltration, and nutrient availability. Additionally, topdressing can help fill in low spots, improve drainage, and reduce thatch buildup [47].

Winter overseeding is the process of seeding a cool-season grass, most commonly perennial ryegrass (*Lolium perene*), temporarily into a well-established warm-season turfgrass during dormant periods of the warm-season turfgrass [48, 49]. Dormancy of warm-season turfgrass can vary but typically takes place at the first hard frost in late fall when soil temperatures start to fall below 10°C [50]. The overseeded cool-season turfgrass should thrive during the colder seasons providing extra traffic tolerance and improved field quality and aesthetics. Greenup from dormancy takes place typically in the spring when the temperature during the day is above 15.5°C and does not go lower than 4.5°C at night [50, 51]. The term used to describe the process when warm-season turfgrasses start to come out of dormancy is ‘spring greenup.’ At this time, a decision must be made whether to chemically remove the overseeded cool-season turfgrass or rely on higher spring and summer temperatures to help naturally transition it out. The earlier the cool-season turfgrass is removed, the quicker the warm-season turfgrass can thrive.

1.5. Sports field performance testing

Sports field performance testing is essential to quantify field conditions, inform management decisions, detect variability, and maintain consistency for optimal field safety and playability. Performance testing measures can vary due to several factors, such as mowing heights, turfgrass species, soil type, climate, and amount of usage. [52-54]. Depending on the state of these characteristics, the performance and safety of athletes can be impacted. An important surface characteristic is soil moisture, which can be determined gravimetrically or volumetrically. It is a measure of the quantity of moisture available in a given weight or volume of soil. Studies have shown that soil moisture plus traffic influences soil compaction, surface hardness, and turfgrass cover and quality, especially on sports fields established on native soils [55, 56]. For example, Straw et al. [57] compared the influence of irrigation on field characteristics of two bermudagrass sports fields established on native and sand rootzones.

Results showed that irrigation significantly decreased mean penetration resistance (i.e., soil compaction) and surface hardness on both rootzones.

Dickson et al. [56] investigated the soil water content of Tifway hybrid bermudagrass sports fields on two rootzones (native and sand) and reported that the hardness increased as soil moisture level of the rootzones decreased. Straw et al. [58] examined the uniformity and spatial variability of soil moisture and irrigation distribution on natural turfgrass sports fields. The authors found that native rootzone soil moisture content had a negative relationship with penetration resistance (i.e., the driest part of the field had highest level of soil compaction). This same relationship was not observed on a sand rootzone field because it was concluded that areas with high penetration resistance had little effect on water infiltration and redistribution.

Surface hardness is a measure of field firmness that is determined by quantifying the maximum deceleration upon impact (Gmax) [59]. In addition to surface hardness, other related field characteristics include force reduction, energy restitution, and vertical deformation. Force reduction reflects the surface's ability to absorb energy upon impact relative to concrete, while energy restitution measures how much energy is returned from the surface upon impact relative to concrete [59]. Vertical deformation measures how much the surface compresses or deforms (in mm) when impacted [59]. Although there are other tools available for measuring these surface characteristics, the most efficient option that takes all measurements simultaneously is the Deltec Field Tester (Deltec Equipment, The Netherlands). This device operates similarly to the Clegg Impact Soil Tester, using a weighted missile of 5 kg with an accelerometer at the base, dropped from a height of 27.9 cm through a tube onto the surface recording the peak acceleration. The Deltec Field Tester also includes a spring to increase the impact time with the surface upon impact [60]. In a study by Lulli et al. [61], the playability of three warm-season turfgrass species was assessed, revealing that zoysiagrass exhibited softer (low surface hardness) and slower (short ball roll distance and low ball rebound) surface characteristics, seashore paspalum had harder (high surface hardness) and faster (long ball roll distance and high ball rebound) surface properties, and bermudagrass demonstrated intermediate attributes in terms of ball roll, surface hardness, traction, vertical deformation, and force reduction.

Shear strength gauges the turfgrasses ability to resist divoting by simulating an athlete planting their foot and pivoting using a field shear test apparatus [44]. The device is typically a torque wrench with cleats attached to its bottom plate, and it is inserted into the ground and rotated, then the maximum torque required to tear the turfgrass is recorded as the shear strength value (in Nm) [62]. If the resistance is excessive (i.e., if the turfgrass has high rotational shear strength), it may lead to injuries for the players as a result of their shoes getting trapped on the surface [63, 64]. Shear strength of a turfgrass can be influenced by the species, root architecture and depth, presence of stolons, and nitrogen content in the turfgrass [37, 65-67]. Fédération Internationale De Football Association (FIFA) has an acceptable range for all of these characteristics on warm and cool season grasses [68]. The acceptable range considered satisfactory for surface hardness, force reduction, vertical deformation, and shear strength of warm-season turfgrasses are as follows: 50-59.9 Gmax or 90.1-95.0 Gmax, 40.0-44.9% or 75.1-80.0%, 3.0-4.0 mm or 11.1-12.0 mm, and 20.0-24.9 Nm or 49.9-55.0 Nm, respectively.

Turfgrass cover and quality are two critical surface characteristics that have an impact on the overall performance of sports fields. They can be measured either through visual observation or objective measurement. Visual observation is a subjective measurement that is rated by the observer on a scale of 1-9 and 0-100 % for quality and cover, respectively (1 being dead turf, 9 is excellent, and 6 acceptable turf). Objectively, they can be measured with the aid of devices of chlorophyll meters like RapidSCAN CS-45 (Holland Scientific Inc., Lincoln, NE) or Crop Circle Model ACS-430 (Holland Scientific Inc., Lincoln NE). These devices are designed to measure the spectral reflectance of near-infrared and red bands to calculate normalized difference vegetation index (NDVI). The NDVI is obtained by applying an equation [(R780 - R670) / (R780 + R670)], where the resulting values range between 0 and 1. A value closer to 1 indicates a healthy and dense turfgrass surface. Turfgrass cover is determined by calculating the percentage of the field area where grass is growing in comparison to the bare surfaces. An objective method of measuring visual cover is with the aid of a light box. The lightbox has a digital camera and four fluorescent bulbs attached to it to ensure a consistent light source during images collection (Ikemura, 2003). Digital images are collected with this device and run through software like SigmaScan Pro for analysis (Systat Software Inc., Chicago, IL).

1.6. Athlete-surface interactions

In the southern United States, natural turfgrass is widely used on sports fields across all levels of competition. Straw et al. [69] listed field characteristics such as turfgrass species, soil moisture and texture, and mowing heights as factors that can possibly influence athlete-surface interactions. Variations in construction, frequency and intensity of use, and management practices can result in differences in sports fields surface characteristics that can impact athlete-surface interactions. These differences may affect athlete biomechanics and their perception of the field, potentially hindering performance or causing injury during competition.

In a study by Guisasola et al. [70], it was found that the peak vertical loading rate, which refers to the force athletes push onto the surface that comes back up to them, was higher on sandy soil compared to clay loam soil. This can affect the running speed and energy use of athletes. Thomson et al. [71] suggested that the interaction between shoe types and sports field characteristics can affect athletes' performance. The authors recommended selecting a shoe type with lower rotational traction to avoid any negative impact on performance.

Orchard et al. [72] reported in a study that, injury risk to athletes had a non-significant correlation with grass type, high evaporation, and low rainfall prior to matches. The authors also suggested that densely growing turfgrass species with high thatch levels, such as bermudagrass, could pose a risk of injury to athletes by trapping their football shoes. Athletes' performance could be affected by their perception of the field they play on, as demonstrated by Straw et al. [73], where perceived within-field variations of turfgrass coverage and surface evenness had the most significant influence on the in-game strategy of the participants.

Studies on athlete-surface interactions often do not fully consider the variability in sports fields, grouping them simply as "natural turfgrass." This can obscure results and make it harder to identify which field characteristics most affect athletes, thus impeding efforts to develop strategies for field construction and management improvements [69]. Traditionally, biomechanical research on athlete-surface interaction has been done in laboratories using force plates to simulate field conditions, but the use of wearable inertial measurement units (IMUs) attached to athletes' ankles allows for this type of research to be conducted on the field.

1.7. Conclusion

This review provides a comprehensive overview of the attributes and management techniques pertaining to warm-season natural turfgrass sports fields, focusing on their influence on field quality and playability. The review also examines the tools and methodologies employed for evaluating surface characteristics and explores the impact of athlete-surface interactions on performance. The initial studies analyzed in this review underscore the significance of proper sports field construction and effective management strategies, including the utilization of plant growth regulators, in ensuring the success of heavily used fields. However, practical insights regarding the implementation of these strategies and their real-world implications for field conditions and athlete performance remain relatively limited.

1.8. References

1. Puhalla J, Krans J, and Goatley M, Sports fields : Design, construction, and maintenance. 2nd ed ed. 2010, Hoboken, N.J., [Lawrence, Kan.]: Wiley ; SportsTurf Managers Association.

2. Turgeon AJ, Turfgrass management. 7th ed ed. 2005, Upper Saddle River, N.J.: Pearson/Prentice Hall.

3. Harlan JR, De Wet JMJ, Huffine WW, and Deakin JR (1970) A guide to the species of cynodon (gramineae). Bulletin of the Oklahoma Agricultural Experiment Station,(No. B-673):37 pp.

4. Harlan JR, de Wet JMJ, and Rawal KM (1970) Geographic distribution of the species of cynodon l. C. Rich (gramineae). East African Agricultural and Forestry Journal. **36**(2):220-226. https://doi.org/10.1080/00128325.1970.11662465

5. Trenholm L, Carrow R, and Duncan R (2000) Mechanisms of wear tolerance in seashore paspalum and bermudagrass. Crop science. **40**(5):1350-1357.

6. Briscoe K, Miller G, Brinton S, Bowman D, and Peacock C (2012) Evaluation of ‘miniverde’bermudagrass and ‘diamond’zoysiagrass putting green establishment using granular fertilizer applications. HortScience. **47**(7):943-947.

7. Bunnell BT, McCarty LB, and Bridges Jr WC (2005) Evaluation of three bermudagrass cultivars and meyer japanese zoysiagrass grown in shade. Int. Turfgrass Soc. Res. J. **10**(Part 2):826-833.

8. Engelke M, Colbaugh P, Reinert J, Marcum K, White R, Ruemmele B, and Anderson S (2002) Registration ofdiamond'zoysiagrass.(registrations of cultivars). Crop science. **42**(1):304-306.

9. Patton AJ (2009) Selecting zoysiagrass cultivars: Turfgrass quality, growth, pest and environmental stress tolerance. Applied Turfgrass Science,(October):1019-01.

10. Qian YL, Engelke MC, and Foster MJV (2000) Salinity effects on zoysiagrass cultivars and experimental lines. Crop Science. **40**(2):488-492. https://doi.org/10.2135/cropsci2000.402488x

11. Wherley B, Skulkaew P, Chandra A, Genovesi A, and Engelke M (2011) Low-input performance of zoysiagrass (zoysia spp.) cultivars maintained under dense tree shade. HortScience. **46**(7):1033-1037.

12. Hinton J (2011) Differences in establishment rate, freeze tolerance, and response to nitrogen fertility rate and mowing height on nine cultivars of zoysiagrass.

13. Patton AJ (2009) Selecting zoysiagrass cultivars: Turfgrass quality, growth, pest and environmental stress tolerance. Applied Turfgrass Science. **6**(1):1-18. https://doi.org/10.1094/ATS-2009-1019-01-MG

14. Wherley BG, Skulkaew P, Chandra A, Genovesi AD, and Engelke MC (2011) Low-input performance of zoysiagrass (zoysia spp.) cultivars maintained under dense tree shade. HortScience horts. **46**(7):1033-1037. https://journals.ashs.org/hortsci/view/journals/hortsci/46/7/article-p1033.xml

15. Riffell S, Engelke M, and Morton S (1995) Performance of three warm-season turfgrasses cultured in shade: Zoysiagrass. Tex. Turfgrass Res. **95**(11):60-65.

16. Lulli F, Volterrani M, Grossi N, Armeni R, Stefanini S, and Guglielminetti L (2012) Physiological and morphological factors influencing wear resistance and recovery in c3 and c4 turfgrass species. Functional Plant Biology. **39**(3):214-221.

17. Minner D, McCullock E, and Steward N (1999) How much is too much. Round II. SportsTURF. **15**(1):46.

18. Brosnan J and Deputy J (2008) Seashore paspalum: Turf management. TM-1, Mãnoa, Hawaii: University of Hawaii at Mãnoa, 8p.

19. Lee G, Duncan RR, and Carrow RN (2004) Salinity tolerance of seashore paspalum ecotypes: Shoot growth responses and criteria. HortScience. **39**(5):1138-1142.

20. Duncan RR and Carrow RN, Seashore paspalum: The environmental turfgrass. 2000: John Wiley & Sons.

21. Guo H, Wang Y, Li D, Chen J, Zong J, Wang Z, Chen X, and Liu J (2016) Growth response and ion regulation of seashore paspalum accessions to increasing salinity. Environmental and Experimental Botany. **131**:137-145. https://www.sciencedirect.com/science/article/pii/S0098847216301356

22. Beard JB and Beard HJ, Beard's turfgrass encyclopedia for golf courses, grounds, lawns, sports fields. 2005: Michigan State University Press.

23. Christians N (2004) Cool-season grasses. Fundamentals of turfgrass management. 2nd ed. John Wiley & Sons, Hoboken, NJ:33-58.

24. Jiang Y, Duncan RR, and Carrow RN (2004) Assessment of low light tolerance of seashore paspalum and bermudagrass. Crop Science. **44**(2):587-594.

25. Hillel D, Introduction to environmental soil physics. 2003: Elsevier.

26. Henderson J, Crum J, Wolff T, and Rogers III 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.

27. Henderson JJ, Sand textured root zones in athletic fields: Turfgrass establishment and constituent selection based on agronomic and engineering properties. 2000: Michigan State University.

28. Association UG, *Green section staff. 2004. Usga recommendations for a method of putting green construction*. 2017.

29. White B (2013) Sand-capping solves everything... Or does it. USGA Green Section Record. **51**(17):1-5.

30. Dyer DW, Wherley BG, McInnes KJ, Thomas JC, Hejl R, and Reynolds WC (2020) Sand-capping depth and subsoil influences on ‘tifway’ bermudagrass response to irrigation frequency and drought. Agronomy Journal. **112**(5):3491-3499. https://acsess.onlinelibrary.wiley.com/doi/abs/10.1002/agj2.20319

31. Carrow RN and Martin Petrovic A (1992) Effects of traffic on turfgrasses. turfgrass. **32**:285-330.

32. Dest W, Ebdon J, and Guillard K (2009) Differentiating between the influence of wear and soil compaction and their interaction of turfgrass stress. International Turfgrass Society Research Journal. **11**(2):1067-1083.

33. Hoffman L, Ebdon J, Dest W, and DaCosta M (2010) Effects of nitrogen and potassium on wear mechanisms in perennial ryegrass: Ii. Anatomical, morphological, and physiological characteristics. Crop science. **50**(1):367-379.

34. Morrish R and Harrison C (1948) Establishment and comparative wear resistance of various grasses and grass-legume mixtures to vehicular traffic. Journal of the American Society of Agronomy.

35. Deaton MT and Williams DW (2010) Overseeding and trinexapac-ethyl effects on tolerance to simulated traffic of four bermudagrass cultivars grown as a sand-based athletic field. HortTechnology. **20**(4):724-729.

36. Thoms AW, Sorochan JC, Brosnan JT, and Samples TJ (2011) Perennial ryegrass (lolium perenne l.) and grooming affect bermudagrass traffic tolerance. Crop science. **51**(5):2204-2211.

37. Canaway P (1983) Effect of rootzone construction on the wear tolerance and playability of eight turfgrass species subjected to football-type wear. Journal-Sports Turf Research Institute.

38. Abbott J, Vitolo D, Porpiqlia P, Brooks R, Peek J, and Pruss S (1991) A new growth regulator for use in warm and cool season turf. HortScience. **26**(6):689.

39. Turgeon AJ, Turfgrass management. 6th ed ed. 2002, Upper Saddle River, N.J.: Prentice Hall.

40. Brosnan JT, Thoms AW, Breeden GK, and Sorochan JC (2010) Effects of various plant growth regulators on the traffic tolerance of 'riviera'bermudagrass (cynodon dactylon l.). HortScience. **45**(6):966-970.

41. McCarty LB, Willis TG, Toler JE, and Whitwell T (2011) 'Tifeagle'bermudagrass response to plant growth regulators and mowing height. Agronomy Journal. **103**(4):988-994.

42. Ervin E and Zhang X (2007) Influence of sequential trinexapac-ethyl applications on cytokinin content in creeping bentgrass, kentucky bluegrass, and hybrid bermudagrass. Crop Science. **47**(5):2145-2151.

43. Ervin EH and Koski A (2001) Trinexapac-ethyl increases kentucky bluegrass leaf cell density and chlorophyll concentration. HortScience. **36**(4):787-789.

44. Rogers III J and Waddington D (1989) The effect of cutting height and verdure on impact absorption and traction characteristics in tall fescue turf. Journal of the Sports Turf Research Institute (United Kingdom).

45. Brosnan J and Deputy J (2007) Managing bermudagrass athletic fields.

46. McCarty LB, Gregg MF, and Toler JE (2007) Thatch and mat management in an established creeping bentgrass golf green. Agronomy Journal. **99**(6):1530-1537.

47. Beard JB. Topdressing overview. in *48th Annual Michigan Turfgrass Conference, January*. 1978.

48. Green RL, Klein GJ, Merino F, and Gibeault V (2004) Influence of fall-applied treatments on spring transition of an overseeded bermudagrass green. HortScience. **39**(2):424-428.

49. Horgan BP and Yelverton FH (2001) Removal of perennial ryegrass from overseeded bermudagrass using cultural methods. Crop Science. **41**(1):118-126.

50. Younger V (1958) Bermudagrass for turf in the southwest. California Turfgrass Culture. **8**:21-23.

51. Stanford R, White R, Krausz J, Thomas J, Colbaugh P, and Abernathy S (2005) Temperature, nitrogen and light effects on hybrid bermudagrass growth and development. Crop science. **45**(6):2491-2496.

52. Orchard JW, Waldén M, Hägglund M, Orchard JJ, Chivers I, Seward H, and Ekstrand J (2013) Comparison of injury incidences between football teams playing in different climatic regions. Open access journal of sports medicine:251-260.

53. Stiles VH, James IT, Dixon SJ, and Guisasola IN (2009) Natural turf surfaces: The case for continued research. Sports Medicine. **39**:65-84.

54. Straw CM, Grubbs RA, Tucker KA, and Henry GM (2016) Handheld versus mobile data acquisitions for spatial analysis of natural turfgrass sports fields. HortScience. **51**(9):1176-1183. https://doi.org/10.21273/HORTSCI11019-16

55. Burbrink CM and Straw CM (2023) Spatiotemporal variability of a stadium football pitch during a professional tournament. Sports Engineering. **26**(1):8. https://doi.org/10.1007/s12283-023-00399-4

56. Dickson KH, Sorochan JC, Brosnan JT, Stier JC, Lee J, and Strunk WD (2018) Impact of soil water content on hybrid bermudagrass athletic fields. Crop Science. **58**(3):1416-1425.

57. Straw CM, Grubbs RA, and Henry GM (2020) Short-term spatiotemporal relationship between plant and soil properties on natural turfgrass sports fields. Agrosystems, Geosciences & Environment. **3**(1):e20043.

58. Straw CM, Carrow R, Bowling W, Tucker K, and Henry G (2018) Uniformity and spatial variability of soil moisture and irrigation distribution on natural turfgrass sports fields. Journal of Soil and Water Conservation. **73**(5):577-586.

59. FIFA (2008) Fifa quality concept for artificial turf. Handbook of test methods.

60. Fleming P, Watts C, Gunn J, and Forrester S. Hardness safety testing of artificial turf. in *Proceedings*. 2020. MDPI. https://doi.org/10.3390/proceedings2020049130

61. Lulli F, de Bertoldi C, Armeni R, Guglielminetti L, and Volterrani M (2014) Warm-season turfgrass species generate sports surfaces with different playability. HortTechnology. **24**(6):749-756.

62. Webb C, Forrester S, and Fleming P (2014) Rotational traction behaviour of artificial turf. Procedia Engineering. **72**:853-858.

63. Thomson A, Bleakley C, Holmes W, Hodge E, Paul D, and Wannop JW (2022) Rotational traction of soccer football shoes on a hybrid reinforced turf system and natural grass. Footwear Science. **14**(1):58-69.

64. Wannop JW, Luo G, and Stefanyshyn D (2011) Footwear traction and lower extremity non-contact injury. Footwear Science. **3**(sup1):S166-S167.

65. Li D, Fang W, and Han L (2011) Nitrogen fertilization influences shear strength and quality of kentucky bluegrass sod grown on clay. Agronomy Journal. **103**(3):751-755.

66. Ross S, Ennos A, and Fitter A (1991) Turf strength and root characteristics of ten turfgrass cultivars. Annals of applied biology. **118**(2):433-443.

67. Roche MB, Loch DS, Poulter RE, and Zeller LC. Measuring the traction profile on sportsfields: Equipment development and testing. in *II International Conference on Turfgrass Science and Management for Sports Fields 783*. 2007.

68. FIFA, *Fifa natural-pitch rating system*, in *Natural Playing Surfaces Quality Programme*. May, 2022: https://digitalhub.fifa.com/m/58aa765dd3e85f26/original/FIFA-natural-pitch-rating-system_EN.pdf. p. 8.

69. Straw CM, Samson CO, Henry GM, and Brown CN (2020) A review of turfgrass sports field variability and its implications on athlete–surface interactions. Agronomy Journal. **112**(4):2401-2417. https://doi.org/10.1002/agj2.20193

70. Guisasola I, James I, Llewellyn C, Bartlett M, Stiles V, and Dixon S (2009) Human–surface interactions: An integrated study. International Turfgrass Society Research Journal. **11**:1097-1106.

71. Thomson A, Whiteley R, Wilson M, and Bleakley C (2019) Six different football shoes, one playing surface and the weather; assessing variation in shoe-surface traction over one season of elite football. PloS one. **14**(4):e0216364.

72. Orchard J, Chivers I, Aldous D, Bennell K, and Seward H (2005) Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass. British journal of sports medicine. **39**(10):704-709.

73. Straw CM, Henry GM, Shannon J, and Thompson JJ (2019) Athletes' perceptions of within-field variability on natural turfgrass sports fields. Precision Agriculture. **20**:118-137.

CHAPTER II

INFLUENCE OF PLANT GROWTH REGULATOR APPLICATION STRATEGIES AND CULTIVATION PRACTICES ON HYBRID BERMUDAGRASS SPORTS FIELDS

2.1. Overview

Trinexapac-ethyl (TE) is a plant growth regulator that is primarily used in turfgrass for reducing mowing requirements due to its ability to limit cell elongation and vertical shoot growth. It is still not well understood how rates and reapplication intervals of TE effect bermudagrass sports field playing characteristics once traffic increases from use, nor is there any available information describing potential benefits of newer cultivation methodologies when implemented in conjunction with TE programs. The objective of this study was to determine how TE rate, reapplication interval, and stoppage, in addition to cultivation practices, influence the playability of trafficked bermudagrass during simulated American football seasons. Research was conducted in summer and fall 2021 at the Texas A&M University Turfgrass Field Laboratory in College Station, TX on two established areas simulating a high school-level field {'TifTuf' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *Cynodon transvaalensis* BurttDavy] on native soil [74% sand, 18% silt, and 9% clay] mowed at 1.9 cm} and a collegiate-level field ['Latitude 36' hybrid bermudagrass mowed at 1.3 cm on a sand-capped soil (97% sand, 2% silt, and 1% clay)]. The same study was replicated under the two different scenarios using the same experimental design, which was a randomized complete block design arranged as a 4x7 factorial. Main plots (11.8 m^2 with 0.5 m border) consisted of three cultivation treatments and an untreated control that began in June using either a rake and/or verticutter bi-monthly or monthly, and stopped once the study areas were overseeded in September with perennial ryegrass (*Lolium perenne*). Subplots (1.6 m^2 with 0.2 m borders) were six TE treatments and an

untreated control applied at a monthly full label rate (0.32 L ha^{-1}) or bi-weekly split label rate (0.16 L ha^{-1}) beginning in June prior to traffic. Once traffic began, TE rates either continued or were split in half, while other TE treatments completely stopped. Traffic was applied using a modified Baldree traffic simulator, and timing and frequency were based on a local high school (home games: 8 passes weekly; away games: 4 passes weekly) and collegiate team's (home games: 4 passes weekly; away games: 2 passes weekly) American football schedule for the 'TifTuf' and 'Latitude 36' scenarios, respectively. Data were collected bi-weekly during the traffic period on normalized difference vegetation index (NDVI; 0-1) and cover (0-100%) metrics, as well as rotational shear strength (Nm), surface hardness (Gmax), force reduction (FR; %), energy restitution (ER; %), and vertical deformation (VD; mm). The results of the study revealed that raking treatment was an effective method for managing turfgrass density. It demonstrated advantages such as shorter application time and minimal negative impact on turfgrass quality when compared to other cultivation treatments. Additionally, the findings indicated that sport field managers can achieve comparable results while reducing costs by discontinuing split rate plant growth regulator (PGR) application before the season, rather than implementing continuous full-rate application.

2.2.Introduction

The goal of sports field management should be to provide safe and playable fields, while also maximizing aesthetic appeal. Foot traffic from athletes is inevitable and induces turfgrass wear that compromises cover and quality [1]. The negative effects of turfgrass wear can be mitigated with conventional sports field management practices, such as routine and proper mowing, fertilization, and irrigation [2, 3]; however, with rapidly declining management budgets and available labor, in addition to increasing field usage and user expectations, sports field managers are seeking more strategies to combat wear stress from foot traffic to maximize turfgrass cover and quality on highly trafficked fields.

Trinexapac-ethyl [4-(cyclopropyl-alpha-hydroxymethylene)-3,5 dioxo-cyclohexanecarboxylic acid ethlyester] (TE) is a class A plant growth regulator (PGR) that is foliar absorbed, limiting cell elongation and vertical development late in the gibberellin production process by inhibiting the conversion of GA_{20} to the physiologically active GA_1 [4]. Practical benefits of TE when applied to turfgrasses include reduced mowing frequency and increased drought tolerance [5] and nutrient retention [6-8]. Reports by Brosnan et al. [9] suggested that TE can also positively influence the traffic tolerance, overall quality, and canopy density of bermudagrass (*Cynodon dactylon* L.). In that study, the effect of several PGRs was evaluated on ‘Riviera’ bermudagrass and plots treated with TE alone or in mixture with other PGRs had a significantly higher turfgrass color, quality, and cover than when other PGRs were used alone. The TE was applied at a rate of 0.096 L product ha^{-1} three times every 21 days before simulated traffic. Williams et al. [10] evaluated the traffic tolerance of several seeded bermudagrasses (Riviera, ‘Princess,’ ‘Transcontinental,’ ‘Savannah,’ and ‘Yukon’) when treated with TE at a rate of 0.096 kg product ha^{-1} and found applications of TE made three times every 21 days before simulated traffic resulted in increased traffic tolerance and improved turfgrass quality. McCarty et. al. [2] conducted a study that observed the effect of bimonthly TE applications for five months at the rate of 0.13 L product ha^{-1} on ‘TifEagle’ bermudagrass performance under three mowing heights, which showed that the turfgrass quality was excellent (8.0-8.4), and root density and tillering ability of bermudagrass significantly increased. The higher root density and tillering ability further highlights that TE could help increase wear tolerance and recovery of bermudagrass sports fields.

Hybrid bermudagrasses must be vegetatively propagated and generally have uniform and dense lateral growth habits compared to other turfgrass species, even without TE applications. This growth habit causes rapid thatch accumulation that can impact sports fields playability if not properly managed [11, 12]. Sand topdressing, aerification, and vertical mowing are common cultivation practices employed by sports field managers to regulate bermudagrass thatch and canopy density [13]. Tow-behind rakes with spring-loaded hardened tines are a newer, more durable, and less aggressive method of dethatching. Although scientific research is currently limited regarding the actual effectiveness of rakes on sports fields playability, they are becoming more widely adopted in practice (personal communication).

Given the potential benefit of improved wear tolerance with TE applications, there is still skepticism surrounding the use of TE during a playing season due to fear of slow growth and in-season recovery from foot traffic. Moreover, there have been beneficial reports of a “rebound” period (i.e., a period of accelerated growth) that occurs if a reapplication of TE is not done before suppression ends [14-16]. Hence, sport field managers are unsure what TE reapplication interval to follow for best results, and there are conflicting opinions to either completely stop TE applications, reduce the rate, or continue applying as usual during a playing season (unpublished preliminary survey data). Furthermore, no science-based information exists to-date comparing sports field playing characteristics between TE rates and reapplication intervals in combination with cultivation practices over the course of a playing season when intense foot traffic is expected.

The objective of this study was to determine the influence of TE application strategies (rate, reapplication interval, and stoppage) and cultivation practices (raking and verticutting) on surface characteristics of overseeded hybrid bermudagrass sports fields during simulated American football seasons. It was hypothesized that season-long application of TE at the full label rate (0.8 L product ha^{-1}) would not provide benefits significantly different from splitting applications into more frequent intervals at lower rates (0.4 L product ha^{-1}), and that the less aggressive raking would provide better results than the more aggressive vertical mowing technique. It is expected that results from the study will provide sports field managers important information regarding TE and cultivation strategies on trafficked sports field.

2.3. Materials and Methods

Experimental setup

Research was conducted from June to Dec of 2021 and 2022 at the Turfgrass Field Laboratory in College Station, TX. The same study was replicated under two different scenarios meant to mimic American football fields and playing seasons. The first scenario was a high school-level field with 'TifTuf' hybrid bermudagrass on native soil (74% sand, 18% silt, and 9% clay) mowed at 1.9 cm, while the second scenario was a collegiate-level field with 'Latitude 36' hybrid bermudagrass mowed at 1.3 cm on a sand-capped soil (97% sand, 2% silt, and 1% clay). Plots were routinely maintained during the study by mowing twice a week and irrigating as needed. A slow-release 23-0-3 fertilizer was applied to each scenario five times from June to Nov at a rate of 48.8 kg ha^{-1}. The experimental design was a split-plot randomized complete block design arranged as a 4x7 factorial with three replications. Main plots (11.8 m^2 with 0.5 m border) consisted of four cultivation treatments and subplots (1.6 m^2 with 0.2 m borders) were seven TE treatments (Table 2.1).

Cultivation treatments

Cultivation treatments were initiated early June 2021 and 2022. Rake cultivation treatments were made bi-weekly using a FDS 6000 Turf Dethatcher (Wood Bay Technologies, Alberta, Canada) towed behind a utility vehicle at a speed of 3.4 km h^{-1}. Verticutting cultivation treatments were made monthly using a Dennis Mower (Howardson Ltd., England). For the rake + verticut treatment, plots were only verticut bi-monthly (i.e., they were not raked and verticut at the same time). Cultivation treatments continued until plots were overseeded with perennial ryegrass at a rate of 488.2 kg ha^{-1} on 22 and 28 Sept 2021 and 2022, respectively. Cultivation treatments were then discontinued to allow for perennial ryegrass germination and establishment.

PGR treatments

Trinexapac-ethyl (Primo Maxx; Syngenta Professional Products, Greensboro, NC) PGR treatments were initiated on 7 and 6 June 2021 and 2022, respectively. They were applied pre-season at either full or split label rates (0.8 and 0.4 L ha^{-1}, respectively), and then once the seasons began rates were continued, halved, or stopped (Table 2.1). Applications were made using a CO_2 pressurized backpack sprayer equipped with a two-nozzle boom (TeeJet XR8008, TeeJet Technologies, TX) and a regulator (Taprite, San Antonio, TX).

Traffic treatments

Traffic was applied using a 1.2 m wide Toro ProCore 648 aerifier (The Toro Company, Bloomington, MN) modified as a Baldree traffic simulator (Kowalewski et al., 2013). It was operated at a speed of 3.2 $kmhr^{-1}$ and the steel studded plates were spaced 0.1 m apart. One pass was made with the traffic simulator to whole plots bi-weekly in June and July each year but was increased to weekly in August each year as the playing seasons approached. The purpose of the pre-season traffic was to simulate moderate field use that might occur under each scenario during summer months.

Traffic timing and intensity during the playing seasons reflected a local high school (TifTuf) and collegiate (Latitude 36) regular season football schedule. In-season traffic began on the TifTuf on 24 and 23 Aug in 2021 and 2022, respectively, until the high school team completed their regular season on 29 Oct in 2021 (i.e., 10 weeks; five home games, four away games, and one bye week). Four passes with the traffic simulator were made to whole plots on Tuesday and Friday (eight total passes) each week a home game was played, whereas two passes were made to whole plots on Tuesday and Friday (four total passes) each week an away game was played. In-season traffic for Latitude 36 began on 3 and 2 Sept in 2021 and 2022, respectively, until the collegiate team completed their regular season on 19 Nov in 2021 (i.e., eleven weeks; nine home games, four away games, and two bye weeks). Four passes with the traffic simulator were made to whole plots on Friday (four total passes) each week a home game was played, whereas two passes were made to whole plots on Friday (two total passes) each week an away game was played.

Due to traffic simulator malfunctioning and becoming unable to operate, only nine and eight weeks of traffic was applied in 2022 on the TifTuf and Latitude, respectively. The traffic intensities between both scenarios differed because it was assumed that a high school field would receive more traffic than a collegiate field, particularly with physical education classes or other school sporting events. No traffic was applied to either scenario during the teams' bye weeks (i.e., when no game was played; 28 and 16 Sept on TifTuf in 2021 and 2022, respectively, and 29 and 15 Oct on Latitude 36 in 2021 and 2022, respectively).

Data collection

Measurements were collected bi-weekly during the trafficking periods and included normalized difference vegetation index (NDVI) using a RapidSCAN CS-45 (Holland Scientific Inc., Lincoln, NE), visual turfgrass cover (0-100%), rotational turfgrass shear strength with a Raw Traction Tester (Raw Stadia, Leicester, United Kingdom), and force reduction (i.e., measure of the ability of the surface to absorb shock or energy), energy restitution (i.e., measure of the energy returned to the tester upon impact), vertical deformation (i.e., measures the depth to which the surface deforms under impact), and surface hardness with a Deltec Field Tester (Deltec Equipment, The Netherlands). The Field Tester device has a 5 kg impact missile with an accelerometer on the bottom that is guided through a tube as it drops from a height of 27.9 cm from the surface. One drop was made in each sub-plot, and it recorded all four variables simultaneously.

Data analysis

Data were analyzed with linear mixed models and repeated-measures ANOVA to determine the effects of PGR and cultivation treatments on the trafficked sports fields. Statistical analyses were conducted in R Studio (v2023.03.0+386) using the ‘nlme,’ ‘stats,’ and ‘emmeans’ packages (RStudio, 2023). When the model showed significant treatment interactions, results were presented for the interaction. Tukey’s HSD test was used as a post hoc comparison test for means separation ($P \leq 0.05$) of significant treatment effects.

2.4. Results

High school field scenario (TifTuf hybrid bermudagrass on native soil)

There was no significant interaction between year and treatment for most measures, except for energy restitution and vertical deformation (Table 2.2). Therefore, both years were combined for the analysis of NDVI, visual turfgrass cover, turfgrass shear strength, force reduction, and surface hardness. Subsequently, separate analyses were conducted for energy restitution and vertical deformation for each year.

Turfgrass measures

The effects of cultivation and PGR treatments on various measures, including NDVI, visual turfgrass cover, and turfgrass shear strength, were examined. However, the results indicated that these treatments did not have a significant impact on these variables. The values obtained for NDVI ranged from 0.56 to 0.58, visual turfgrass cover ranged from 69.0 to 71.3%, and turfgrass shear strength ranged from 35.9 to 36.9 Nm.

Soil measures

Cultivation and PGR treatments had a significant effect on surface hardness and force reduction (Table 2.3). The untreated cultivation treatment had the lowest surface hardness (79.9 Gmax) but it was statistically similar to verticutting (81.9 Gmax) and raking (82.2 Gmax). The verticutting + raking treatment had the highest surface hardness value (85.8 Gmax) and was significantly higher than the untreated and verticutting treatments (Table 2.3). For PGR treatments, only the full rate before and during traffic (79.6 Gmax) had a statistically different surface hardness value from the untreated control (85.7 Gmax), and the only differences between PGR treatments were it and split applications made at half rate during traffic (85.9 Gmax) (Table 2.3). The separation of means for force reduction did not show any significant differences between main effects. However, the interaction between cultivation treatments and date for force reduction was significant at two weeks after traffic when significant differences were detected between the untreated (59.7%) and vericutting + raking (59.9%) treatments and raking (51.7%) and verticutting (52.6%) treatments (data not shown).

Cultivation and PGR treatments had a significant effect on energy restitution and vertical deformation in 2021 (Table 2.4). Energy restitution for the untreated cultivation treatment (17.8%) was statistically similar to verticutting (18.0%) and raking (18.3%) but was significantly lower than verticutting + raking (19.0%) (Table 2.4). Likewise, only the PGR treatment with full rate before and during traffic (17.7%) had a significantly lower energy restitution than the untreated control (19.3%), but it was statistically similar to all other PGR treatments (Table 2.4). The untreated cultivation treatment (6.4 mm) had a significantly higher vertical deformation than other cultivation treatments, which were similar to one another (Table 2.4). All the PGR treatments were statistically similar, yet the untreated (5.7 mm) was significantly lower than full rate before and during traffic (6.2 mm) and full rate before and half rate during traffic (6.2 mm) treatments (Table 2.4).

In 2022, cultivation significantly influenced energy restitution and vertical deformation, although the interaction between cultivation and PGR for vertical deformation was significant. The untreated cultivation treatment had similar energy restitution as raking and verticutting (8.9, 8.4, 8.4%, respectively) but significantly higher values than verticutting + raking (8.0%). Nevertheless, all three cultivation treatments were statistically similar (Table 2.4). The combination of the untreated cultivation treatment and PGR at full rate before and stopped during traffic (11.0 mm) had the lowest vertical deformation value that was significantly different than the combinations of verticutting + raking and PGR at split rate before and half split rate during traffic (16.9 mm) (Fig. 1).

Collegiate field scenario (Latitude 36 hybrid bermudagrass on sand-capped rootzone)

There was no significant year by treatment interaction for any measures except energy restitution and vertical deformation. Both years were combined in the analysis for NDVI, visual turfgrass cover, turfgrass shear strength, surface hardness, and force reduction and separate analyses were done for both years of energy restitution and vertical deformation (Table 2.5).

Turfgrass measures

The effect of cultivation treatments was significant on NDVI and turfgrass cover, but not turfgrass shear strength (Table 2.6). The verticutting treatment had significantly lower NDVI (0.70) compared to the untreated control, which had the highest NDVI (0.72) (Table 2.6). The verticutting treatment resulted in significantly lower turfgrass cover (87.8%) compared to the untreated (89.7%) and raking treatments (89.1%) (Table 2.6). Plant growth regulator treatments had no significant effect on turfgrass cover and shear strength, yet did on NDVI. All PGR treatment applications, except the full rate before and during traffic, resulted in significantly higher NDVI values than the untreated (Table 2.6). All PGR treatments had statistically similar NDVI, with the split rate before and stopped during traffic, split rate before and during traffic, and full rate before and stopped during having the highest NDVI (0.71; Table 2.6).

Soil measures

The cultivation and PGR interaction was significant (Table 2.7). For surface hardness, the combination of the untreated cultivation and PGR treatments had the highest value (63.1 Gmax), which was significantly higher than the combinations of verticutting and split PGR rate before and during traffic (56.7 Gmax), raking and split PGR rate before and stopped during traffic (56.4

Gmax), verticutting and full rate PGR before and stopped during traffic (55.7 Gmax), verticutting + raking and split PGR rate before and during traffic (55.7 Gmax), and verticutting and full rate PGR before and during traffic (53.1 Gmax), (Table 2.7; Fig. 2). The combination of untreated cultivation and PGR treatments had the lowest force reduction (70.3%), which was significantly lower than the combination of verticutting and full PGR rate before and during traffic. (76.0%) (Table 2.7; Fig. 3).

In 2021, cultivation and PGR main effects were significant for both energy restitution and vertical deformation, and a significant interaction between cultivation and PGR was determined for vertical deformation (Table 2.8). The untreated cultivation treatment had the highest energy restitution (8.2%) that was significantly higher than raking (7.7%) and verticutting (7.5%). The untreated PGR treatment also had the highest energy restitution (8.6%) that was significantly different between full PGR rate before and half rate during traffic (7.6%), split PGR rate before and during traffic (7.5%), and full PGR rate before and stopped during traffic (7.4%) (Table 2.8). The combination of verticutting and full PGR rate before and during traffic resulted in the highest vertical deformation (10.1 mm) (Fig. 4), which was significantly different than the combinations of untreated cultivation and PGR (8.4 mm), untreated cultivation and split PGR rate before and during traffic (8.7 mm), raking and untreated PGR (8.6 mm), untreated cultivation and full PGR rate before and stopped during traffic (8.7 mm), and verticutting and split PGR rate before and halved during traffic (8.4 mm), (Fig. 4).

In 2022, only PGR treatments had significant effects on energy restitution and vertical deformation. The untreated PGR treatment (9.5%) had a similar energy restitution as split PGR rate before and stopped during traffic (9.6%), but both were significantly lower than split PGR rate before and during traffic (10.4%), full PGR rate before and during traffic (10.3%), full PGR rate before and halved during traffic (10.3%), and full PGR rate and stopped during traffic treatments. (10.3%). Similarly, the untreated PGR treatment had the highest vertical deformation (6.9 mm), which was significantly different than the full PGR rate before and halved during traffic (6.2 mm) and full PGR rate and stopped during traffic (5.9 mm) treatment (Table 2.8).

2.5. Discussion

Cultivation treatments had the most significant impact on NDVI and turfgrass cover in the collegiate sports field scenario. All cultivation treatments consistently resulted in lower NDVI and turfgrass cover values compared to the untreated control. Among the cultivation treatments, verticutting and verticutting + raking resulted in the most notable decline. Verticutting + raking yielded a higher NDVI and turfgrass cover compared to verticutting alone, although this difference was not statistically significant. A separate study conducted on lawns without traffic examined the effects of three dethatching techniques: verticutting, power-raking (a specialized machine that uses blades to remove thatch, but is less aggressive than verticutting), and verticutting + power-raking [17]. The results of that study demonstrated that the combined use of verticutting and power-raking produced the best outcomes by not only eliminating thatch but also improving soil permeability and promoting deeper root growth [17]. These factors may have led to the increased NDVI and turfgrass cover observed with the verticutting + raking treatment in this study. However, it is worth noting that this effect was not observed in the high school sports field scenario, suggesting that other factors like turfgrass species and soil type may have an impact.

It was observed that PGR had significant effect on NDVI in collegiate-level field scenerio. All PGR treatments, except for the full PGR rate before and during traffic treatment, resulted in a significant increase in NDVI compared to the untreated control. The split label rates showed similar effects to the full label rates, suggesting that dividing the application or even stopping it before the season could produce comparable results to applying full rates throughout the entire season. This finding is consistent with a study conducted by Fagerness and Yelverton [15], which demonstrated that different rates of TE (0.107 and 0.071 kg a.i. ha^{-1}) on Tifway hybrid bermudagrass had no significant effect on turfgrass quality. It supports the use of reduced rates of TE, potentially providing cost-saving benefits for sports field managers. However, in the high school scenario, none of the PGR treatments had a significant effect on NDVI compared to the untreated control. This contrasts with the results of a study involving TifTuf (under the experimental name 'DT-1' in the study) and TE at a rate of 0.93 kg product ha^{-1}, where TE application significantly reduced turfgrass quality compared to the untreated control. It's important to note that the duration of the present study differed from theirs, and traffic was also applied, which may have influenced the results.

The results indicated that the effects of treatments varied for the soil measures in both field conditions. In the collegiate field scenario, the interaction between the untreated controls resulted in the hardest surface, with a higher surface hardness and lower force reduction. In contrast, the combination of verticutting and full PGR rate before and during traffic led to the softest surface the absorbed more energy upon impact. This observation highlights the influence of cultivation treatments in loosening soil at the surface. Other studies that involved cultivation treatments like verticutting only measured turfgrass visual qualities and ball roll distance [18-20].. Conversely, under the high school scenario, the untreated cultivation exhibited the softest surface, with a surface hardness value of 79.9 Gmax. There were no significant differences between verticutting and raking treatments. However, the verticutting + raking treatment resulted in the hardest surface. This outcome may be attributed to growth characteristics between the two turfgrass varieties, difference in mowing height, or other factors.

In 2021, the untreated cultivation and PGR treatments resulted in higher energy restitution in the collegiate field scenario. However, the split PGR rates, except for split PGR rate before and during traffic, exhibited similar effects to the untreated control. These treatments reduced energy restitution due to their impact on surface hardness. Additionally, the significant interaction between cultivation and PGR treatments led to verticutting + full PGR rate before and during traffic treatment having the softest surface with highest vertical deformation. Conversely, in 2022, energy restitution increased due to PGR application, but only the split PGR rate stopped during traffic had similar effect as the untreated control. This trend was also observed in terms of vertical deformation, where the untreated control and split PGR rates resulted in the softest surface. The difference in energy restitution between the two years may be attributed to the presence of overseeded perennial ryegrass in 2021, which did not establish in 2022 due to environmental conditions.

In the high school scenario in 2021, the verticutting + raking treatment significantly increased energy restitution and reduced vertical deformation compared to the untreated control. Additionally, all PGR treatments, except for full PGR rate before and during traffic, exhibited higher energy restitution and lower vertical deformation values similar to the untreated control. In 2022, PGR applications had no significant effect on energy restitution. However, the effect of cultivation treatments was opposite, similar to the collegiate-level field. We hypothesize that the absence of overseeded grass might have influenced this change in results.

2.6. Conclusion

This study evaluated the impact of cultivation treatments and varying PGR treatment rates and reapplication intervals, on turfgrass performance. Parameters assessed included NDVI, visual cover, shear strength, surface hardness, force reduction, energy restitution, and vertical deformation. The study examined both high school and collegiate field scenarios, revealing more pronounced treatment effects on the sand-capped collegiate-level field compared to the native soil high school field.

The results indicated that cultivation treatments had a negative impact on the quality of the collegiate field, there were no significant surface performance differences between verticutting, raking, verticutting + raking under the two field scenarios examined in this study. The application of PGR at the full label rate did not yield significantly better results compared to split rates. In fact, using the full rate of PGR throughout the study had a negative impact on the NDVI of the collegiate-level field. From a turfgrass quality perspective, our results did not demonstrate any significant benefits of PGR application on heavily trafficked fields, such as the high school field scenario. Furthermore, overseeding appeared to have an influence on some surface characteristics, as evidenced by the differences in surface hardness between the two years of the study. It is important to note that many of the significant differences observed among treatments in the measured variables were not substantial and still fell within acceptable ranges set by professional leagues of sports other than American football [21].

In our study, different traffic levels, hybrid bermudagrass cultivar, soil type, and mowing heights were used for the two field scenarios. These could have been responsible for some of the differences we observed between the two field conditions. Further research in this area should factor these differences in and the impacts they might have on turfgrass surface characteristics.

In addition, aerification can be incorporated into the study to mitigate the effects of soil compaction, which could potentially mask the treatment effects.

Raking provides effective results comparable to verticutting but with less aggression and minimal impact on turfgrass quality, while PGR applications at split rates offer similar benefits to full rates. Additionally, implementing rake treatment requires less manpower and time compared to verticutting, making it a practical choice for sports field management. Furthermore, there is no significant benefit in continuing PGR application throughout the season compared to stopping it when traffic begins. This allows sports field managers to save costs while achieving comparable results.

Table 2.1. Main plot and sub-plot treatments.

Treatments	**Details**
Main plot (cultivation)	
Untreated control	No rake or verticut
Raking	Bi-weekly
Verticutting	Bi-monthly
Verticutting+ raking	Bi-monthly verticut + bi-weekly raking
Sub-plot (PGR)	
Untreated	No PGR
Full rate continued	Monthly application at full label rate for the entire study duration
Full rate halved	Monthly application at full label rate, and then monthly application at half label rate during traffic
Full rate stopped	Monthly application at full label rate, and then stop during traffic
Split rate continued	Bi-weekly split application at full label rate for entire study duration
Split rate halved	Bi-weekly split application at full label rates, and then bi-weekly application at half label rate during traffic
Split rate stopped	Bi-weekly split application at full label rate, and then stop during traffic

Notes: plant growth regulator, PGR; All cultivation and trinexapac-ethyl treatments began in June of each year. Full label rate is 0.8 L ha^{-1}.

Table 2.2. Analysis of Variance (ANOVA) results for main effects and interactions of cultivation, plant growth regulator (PGR) and date on mean normalized difference vegetation index (NDVI), turfgrass cover, turfgrass shear strength, surface hardness, force reduction, energy restitution, and vertical deformation in a high school sports field scenario (TifTuf hybrid bermudagrass on native soil).

	NDVI	**Turfgrass cover**	**Shear**	**Surface hardness**	**Force reduction**	**Energy restitution**		**Vertical deformation**	
						2021	2022	2021	2022
Cultivation (C)	NS	NS	NS	***	*	*	*	***	***
PGR	NS	NS	NS	***	*	**	NS	**	NS
Date (D)	NS	***	*	***	***	***	***	***	***
C x PGR	NS	NS	NS	NS	NS	NS	NS	NS	***
C x D	NS	NS	NS	NS	*	NS	NS	NS	NS
PGR x D	NS	NS	NS	NS	NS	NS	NS	NS	NS
C x PGR x D	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS, not significant at $P \leq 0.05$

Table 2.3. Effects of cultivation and plant growth regulator (PGR) treatments on mean surface hardness and force reduction of TifTuf hybrid bermudagrass

Treatments	**Surface hardness (Gmax)**	**Force reduction (%)**
Cultivation		
Untreated control	79.9 ± 1.1 a	61.6 ± 0.6
Raking	82.2 ± 1.1 ab	59.6 ± 0.7
Verticutting	81.9 ± 1.1 a	59.8 ± 0.7
Verticutting + raking	85.8 ± 1.1 b	60.0 ± 0.5
PGR		
Untreated	85.7 ± 1.6 b	58.5 ± 0.9
Full rate continued	79.7 ± 1.4 a	61.6 ± 0.8
Full rate halved	81.0 ± 1.4 ab	61.0 ± 0.8
Full rate stopped	80.5 ± 1.4 ab	60.7 ± 0.9
Split rate continued	81.0 ± 1.4 ab	60.9 ± 0.8
Split rate halved	85.9 ± 1.5 b	59.0 ± 0.8
Split rate stopped	83.6 ± 1.4 ab	59.8 ± 0.8

Note: Means within a column with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

Table 2.4. Effects of cultivation and plant growth regulator treatments on mean energy restitution (2021 & 2022) and vertical deformation (2021) of TifTuf hybrid bermudagrass

Treatments	**Energy restitution (%) (2021)**	**Energy restitution (%) (2022)**	**Vertical Deformation (mm) (2021)**
Cultivation			
Untreated control	17.8 ± 0.3 a	8.9 ± 0.3 b	6.4 ± 0.1 b
Raking	18.3 ± 0.3 ab	8.4 ± 0.3 ab	5.9 ± 0.12 a
Verticutting	18.0 ± 0.3 ab	8.4 ± 0.3 ab	5.9 ± 0.1 a
Verticutting + raking	19.0 ± 0.4 b	8.0 ± 0.3 ab	5.7 ± 0.1 a
PGR			
Untreated	19.3 ± 0.6 b	8.2 ± 0.4	5.7 ± 0.2 a
Full rate continued	17.7 ± 0.4 a	8.7 ± 0.5	6.2 ± 0.2 b
Full rate halved	17.7 ± 0.4 ab	8.3 ± 0.4	6.2 ± 0.2 b
Full rate stopped	17.8 ± 0.4 ab	8.4 ± 0.4	6.0 ± 0.1 ab
Split rate continued	17.9 ± 0.4 ab	8.9 ± 0.5	5.9 ± 0.1 ab
Split rate halved	19.1 ± 0.5 ab	8.1 ± 0.3	5.8 ± 0.2 ab
Split rate stopped	18.3 ± 0.4 ab	8.4 ± 0.4	6.0 ± 0.2 ab

Note: Means within a column with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

Table 2.5. Analysis of Variance (ANOVA) for main effects and interactions of cultivation, plant growth regulator (PGR) and date on mean normalized difference vegetation index (NDVI), turfgrass cover, turfgrass shear strength, surface hardness, force reduction, energy restitution, and vertical deformation in a collegiate sports field scenario (Latitude 36 hybrid bermudagrass on sand-capped soil).

	NDVI	Turfgrass cover	Shear	Surface hardness	Force reduction	Energy restitution		Vertical deformation	
						2021	2022	2021	2022
Cultivation (C)	***	**	NS	NS	NS	**	NS	*	NS
PGR	***	NS	NS	***	***	**	***	***	***
Date (D)	***	***	***	***	***	***	***	***	***
C x PGR	NS	NS	NS	***	***	NS	NS	*	NS
C x D	NS	NS	NS	NS	NS	NS	NS	NS	NS
PGR x D	NS	NS	NS	NS	NS	NS	NS	NS	NS
C x PGR x D	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS, not significant at $P \leq 0.05$

Table 2.6. Effects of cultivation and plant growth regulator treatments on mean normalized difference vegetation index (NDVI), turfgrass cover, and turfgrass shear strength of Latitude hybrid bermudagrass grass.

Treatment	**NDVI**	**Turfgrass cover (%)**	**Shear (Nm)**
Cultivation			
Untreated control	0.72 ± 0.0041 c	89.7 ± 0.39* b	37.3 ± 0.44
Raking	0.71 ± 0.0043 ab	89.1 ± 0.40 b	36.6 ± 0.44
Verticutting	0.70 ± 0.0052 a	87.8 ± 0.46 a	37.0 ± 0.50
Verticutting + raking	0.71 ± 0.0044 b	88.7 ± 0.36 ab	37.0 ± 0.44
PGR			
Untreated	0.69 ± 0.0060 a	88.5 ± 0.53	38.1 ± 0.65
Full rate continued	0.71 ± 0.0071 ab	88.7 ± 0.53	36.8 ± 0.62
Full rate halved	0.71 ± 0.0058 b	89.2 ± 0.55	36.9 ± 0.62
Full rate stopped	0.71 ± 0.0059 b	88.9 ± 0.53	36.2 ± 0.58
Split rate continued	0.71 ± 0.0056 b	89.0 ± 0.53	36.7 ± 0.61
Split rate halved	0.71 ± 0.0057 b	88.9 ± 0.55	36.8 ± 0.56
Split rate stopped	0.71 ± 0.0058 b	88.7 ± 0.52	37.4 ± 0.56

Note: Means within a column with a common letter are not significantly different according to Tukey’s HSD test (α = .05). Normalized difference vegetation index, NDVI; turfgrass cover, TC; and turfgrass shear strength.

* standard error

Table 2.7. Effects of cultivation and plant growth regulator treatments on mean surface hardness, force reduction, and vertical deformation (2021 only) of Latitude hybrid bermudagrass

Treatments	**Surface hardness (Gmax)**	**Force reduction (%)**	**Vertical deformation (mm) (2021 only)**
Untreated control + Untreated	63.1 ± 2.5 d	70.3 ± 1.2 a	8.4 ± 0.6 ab[b]
Untreated control + Full rate continued	57.7 ± 1.4 abcd	72.5 ± 0.8 ab	8.9 ± 0.4 abc
Untreated control + Full rate halved	57.2 ± 1.1 abcd	73.2 ± 0.7 ab	9.2 ± 0.4 ab
Untreated control + Full rate stopped	59.2 ± 1.3 abcd	72.1 ± 0.8 a	8.7 ± 0.4 ab
Untreated control + Split rate continued	59.3 ± 1.4 abcd	72.2 ± 0.9 ab	8.7 ± 0.3 ab
Untreated control + Split rate halved	59.4 ± 1.4 bcd	71.9 ± 0.8 a	8.9 ± 0.4 abc
Untreated control + Split rate stopped	58.0 ± 1.2 abcd	72.9 ± 0.8 ab	9.3 ± 0.4 abc
Rake + Untreated	61.7 ± 1.6 bcd	70.6 ± 0.9 a	8.6 ± 0.4 ab
Rake + Full rate continued	59.3 ± 1.5 abcd	72.1 ± 0.9 a	9.6 ± 0.6 abc
Rake + Full rate halved	58.0 ± 1.2 abcd	72.7 ± 0.8 ab	9.3 ± 0.5 abc
Rake + Full rate stopped	58.1 ± 1.3 abcd	72.6 ± 0.8 ab	9.5 ± 0.5 abc
Rake + Split rate continued	57.2 ± 1.0 abcd	73.0 ± 0.6 ab	9.7 ± 0.4 abc
Rake + Split rate halved	58.1 ± 1.3 abcd	72.7 ± 0.8 ab	9.1 ± 0.5 abc
Rake + Split rate stopped	56.4 ± 1.1 abc	73.7 ± 0.7 ab	9.5 ± 0.5 abc
Verticutting + Untreated	62.3 ± 1.8 cd	70.3 ± 0.9 a	8.8 ± 0.4 abc
Verticutting + Full rate continued	53.1 ± 1.0 a	76.0 ± 0.7 b	10.1 ± 0.5 c
Verticutting + Full rate halved	57.2 ± 1.1 abcd	73.2 ± 0.7 ab	9.0 ± 0.4 abc
Verticutting + Full rate stopped	55.7 ± 1.0 ab	74.0 ± 0.7 ab	9.8 ± 0.4 bc
Verticutting + Split rate continued	56.7 ± 1.0 abc	73.5 ± 0.6 ab	9.2 ± 0.4 abc
Verticutting + Split rate halved	62.1 ± 1.5 cd	70.4 ± 0.8 a	8.4 ± 0.5 a
Verticutting + Split rate stopped	59.8 ± 1.3 bcd	71.8 ± 0.8 a	8.9 ± 0.3 abc
Verticutting + raking + Untreated	59.6 ± 1.3 bcd	71.8 ± 0.8 a	9.0 ± 0.4 abc
Verticutting + raking + Full rate continued	59.7 ± 1.2 bcd	71.6 ± 0.7 a	9.1 ± 0.4 abc
Verticutting + raking + Full rate halved	58.2 ± 1.1 abcd	72.6 ± 0.7 ab	9.1 ± 0.4 abc

Verticutting + raking + Full rate stopped	58.1 ± 1.2 abcd	72.9 ± 0.8 ab	9.3 ± 0.4 abc
Verticutting + raking + Split rate continued	55.7 ± 1.1 ab	74.0 ± 0.7 ab	9.5 ± 0.4 abc
Verticutting + raking + Split rate halved	60.6 ± 1.4 bcd	72.2 ± 1.2 ab	8.8 ± 0.4 abc
Verticutting + raking + Split rate stopped	61.5 ± 1.2 bcd	70.6 ± 0.7 a	9.1 ± 0.4 abc

Note: Means within a column with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

Table 2.8. Effects of cultivation and plant growth regulator treatments on mean energy restitution (2021 & 2022) and vertical deformation (2022) of Latitude hybrid bermudagrass

Treatment	**Energy restitution (%) (2021)**	**Energy restitution (%) (2022)**	**Vertical deformation (mm) (2022)**
Cultivation			
Untreated control	8.2 ± 0.3 b	10.3 ± 0.2	6.5 ± 0.2
Raking	7.7 ± 0.2 a	10.0 ± 0.2	6.4 ± 0.2
Verticutting	7.5 ± 0.3 a	9.9 ± 0.2	6.4 ± 0.2
Verticutting + raking	7.7 ± 0.2 ab	9.9 ± 0.2	6.3 ± 0.2
PGR			
Untreated	8.6 ± 0.5 b	9.5 ± 0.2 a	6.9 ± 0.3 c
Full rate continued	7.8 ± 0.3 ab	10.3 ± 0.3 b	6.4 ± 0.2 abc
Full rate halved	7.6 ± 0.3 a	10.3 ± 0.3 b	6.2 ± 0.2 ab
Full rate stopped	7.4 ± 0.3 a	10.3 ± 0.3 b	5.9 ± 0.2 a
Split rate continued	7.5 ± 0.3 a	10.4 ± 0.3 b	6.3 ± 0.2 abc[c]
Split rate halved	7.9 ± 0.3 ab	9.7 ± 0.3 ab	6.6 ± 0.2 bc
Split rate stopped	7.9 ± 0.3 ab	9.6 ± 0.3 a	6.6 ± 0.2 bc

Note: Means within a column with a common letter are not significantly different according to Tukey's HSD test (α = .05).

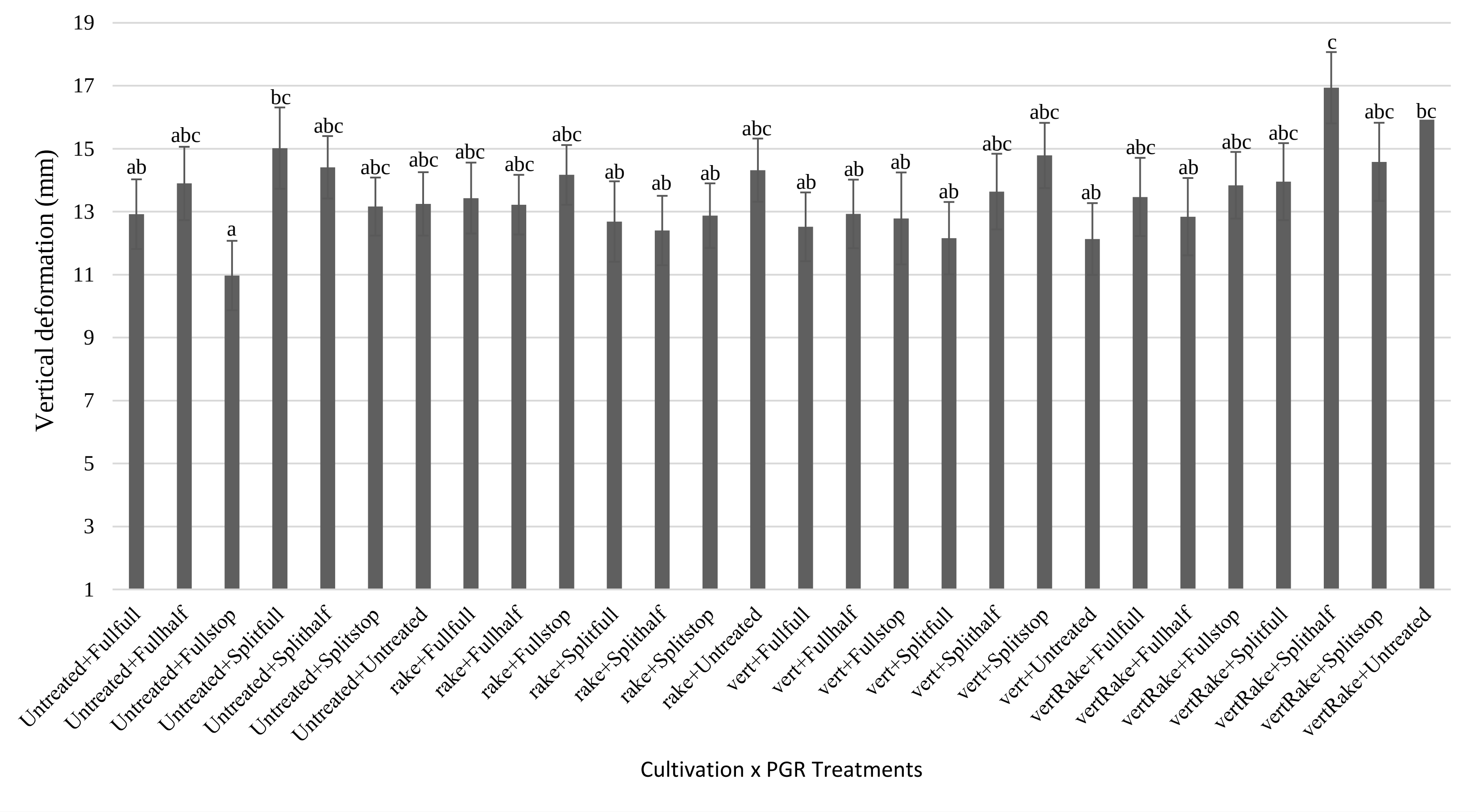

Figure. 1: Effects of PGR and cultivation treatments interaction on mean vertical deformation of TifTuf hybrid bermudagrass in 2022. Vert, verticutting; VertRake, verticutting + rake; Fullfull, full rate continued; Fullhalf, full rate halved; Fullstop, full rate stopped; Splitfull, split rate continued; Splithalf, split rate halved; Splitstop, split rate stopped. Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

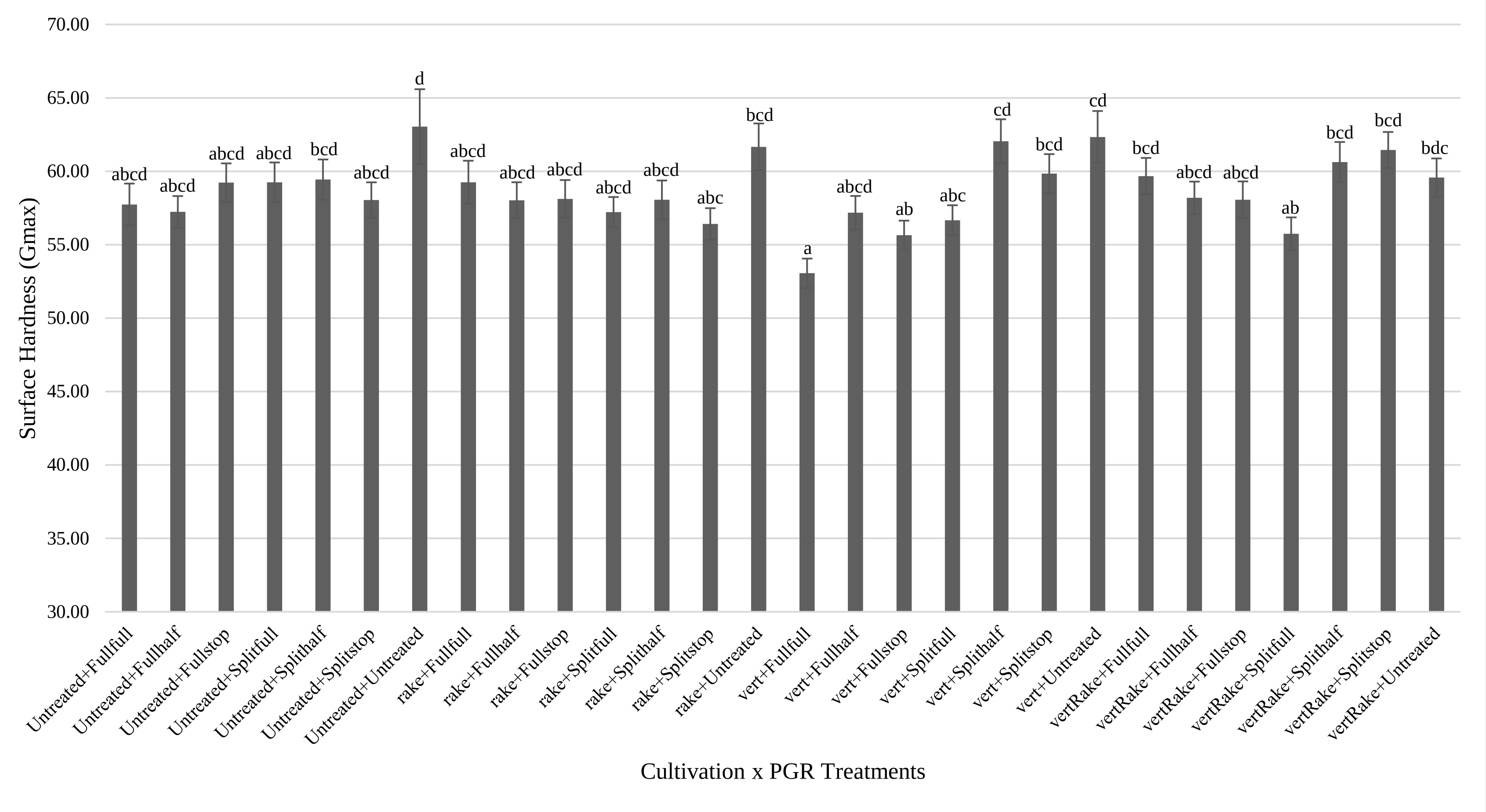

Figure 2: Effects of PGR and cultivation treatments interaction on mean surface hardness of Latitude hybrid bermudagrass. Vert, verticutting; VertRake, verticutting + rake; Fullfull, full rate continued; Fullhalf, full rate halved; Fullstop, full rate stopped; Splitfull, split rate continued; Splithalf, split rate halved; Splitstop, split rate stopped. Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

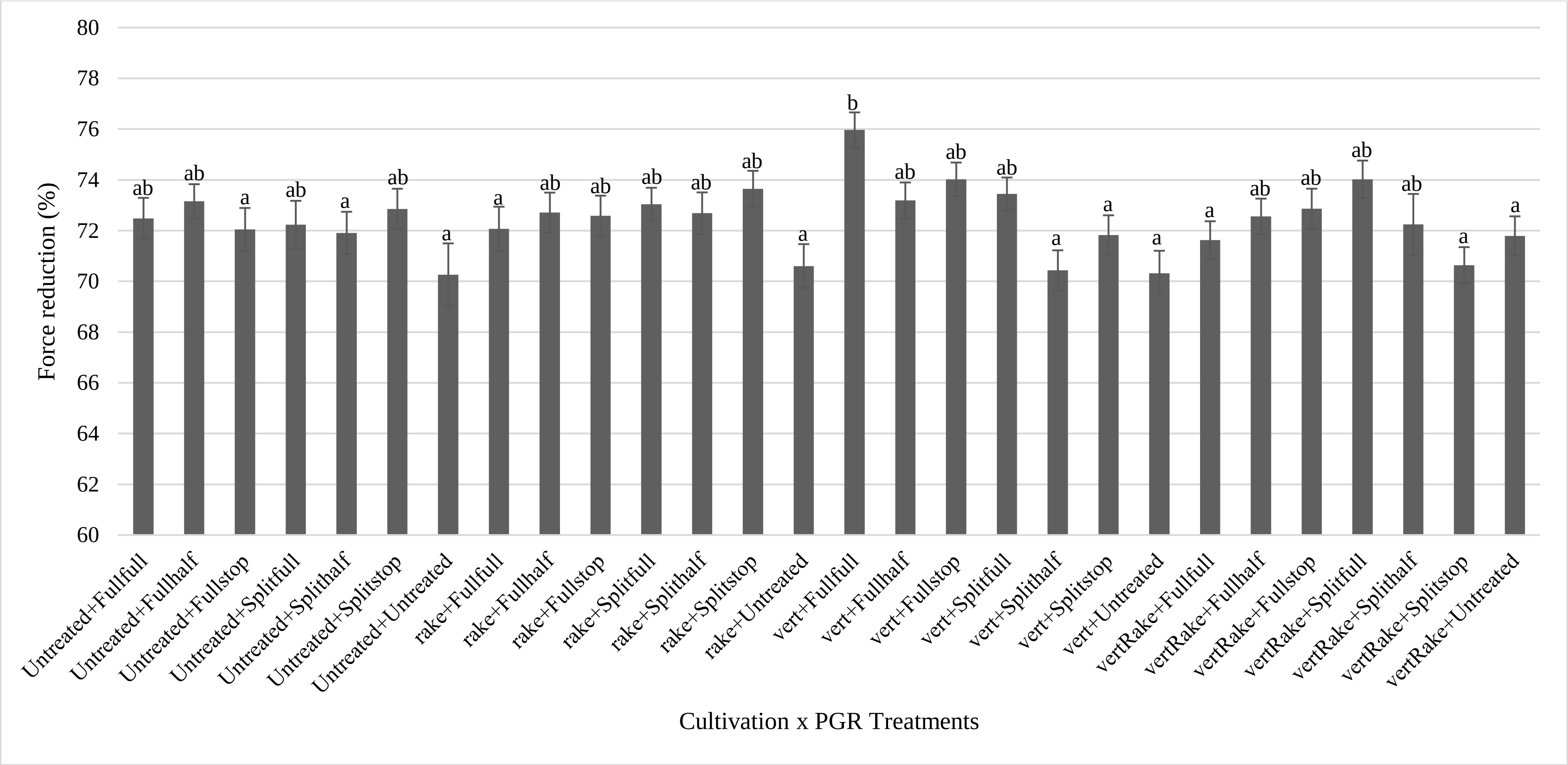

Figure 3: Effects of PGR and cultivation treatments interaction on mean force reduction of Latitude hybrid bermudagrass. Vert, verticutting; VertRake, verticutting + rake; Fullfull, full rate continued; Fullhalf, full rate halved; Fullstop, full rate stopped; Splitfull, split rate continued; Splithalf, split rate halved; Splitstop, split rate stopped. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

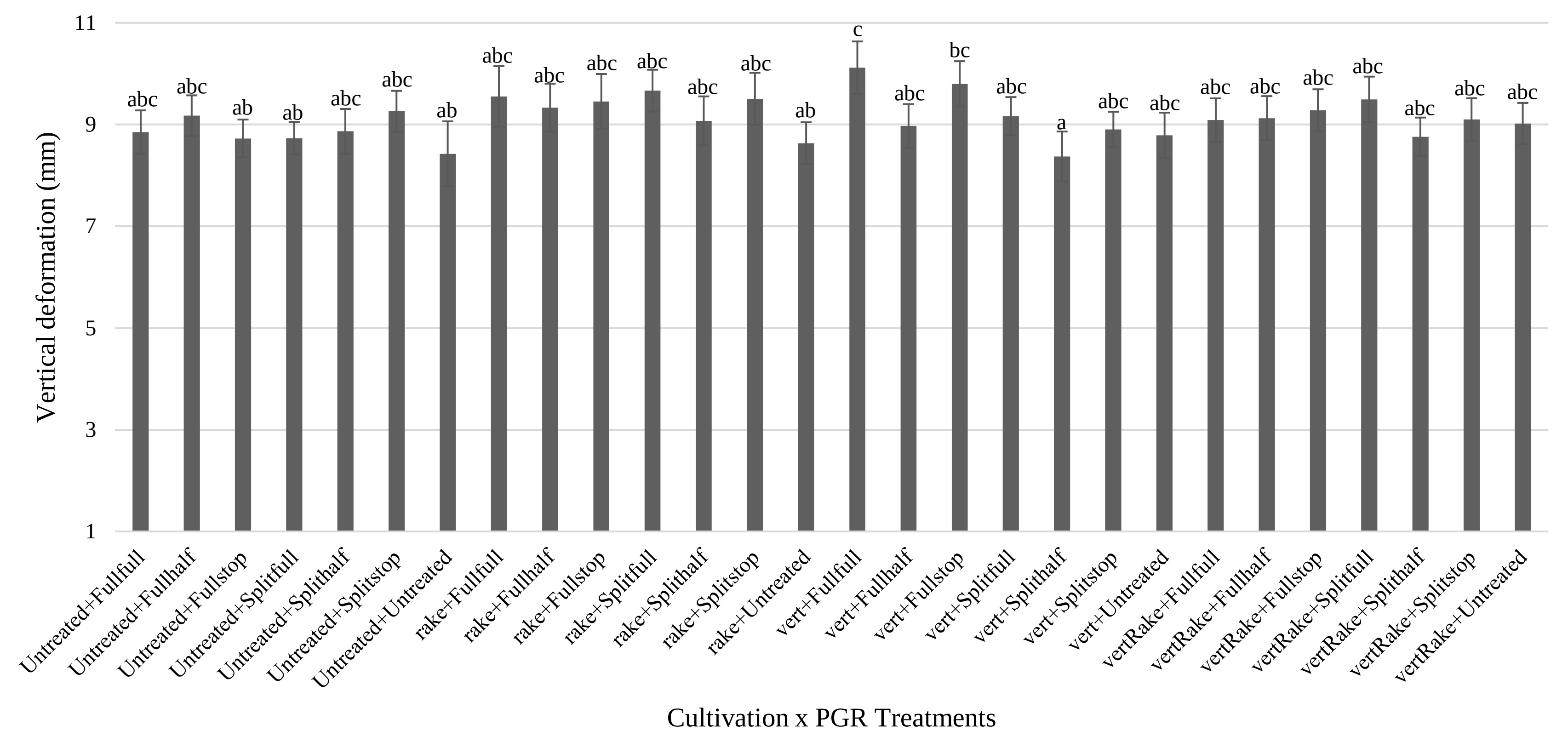

Figure 4: Effects of PGR and cultivation treatments interaction on mean vertical deformation of Latitude hybrid bermudagrass in 2021. Vert, verticutting; VertRake, verticutting + rake; Fullfull, full rate continued; Fullhalf, full rate halved; Fullstop, full rate stopped; Splitfull, split rate continued; Splithalf, split rate halved; Splitstop, split rate stopped. Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

2.7. References

1. Carrow RN and Martin Petrovic A (1992) Effects of traffic on turfgrasses. turfgrass. **32**:285-330.

2. McCarty LB, Willis TG, Toler JE, and Whitwell T (2011) 'Tifeagle'bermudagrass response to plant growth regulators and mowing height. Agronomy Journal. **103**(4):988-994.

3. Mascitti EC, McNitt AS, and Serensits TJ (2017) Divot resistance of thick cut sod as influenced by preharvest nitrogen and sand topdressing. International Turfgrass Society Research Journal. **13**(1):330-337.

4. Adams R, Kerber E, Pfister K, and Weiler E. Studies on the action of the new growth retardant cga 163'935 (cimectacarb). in *Progress in Plant Growth Regulation: Proceedings of the 14th International Conference on Plant Growth Substances, Amsterdam, 21–26 July, 1991*. 1992. Springer.

5. Hejl RW, Wherley BG, Thomas JC, and White RH (2015) Irrigation water quality and trinexapac-ethyl effects on bermudagrass response to deficit irrigation. HortScience. **50**(7):1081-1087.

6. McCullough PE, Liu H, McCarty LB, and Toler JE (2007) Trinexapac-ethyl application regimens influence growth, quality, and performance of bermuda grass and creeping bentgrass putting greens. Crop science. **47**(5):2138-2144.

7. McCullough PE, Liu H, McCarty LB, Whitwell T, and Toler JE (2006) Nutrient allocation of 'tifeagle'bermudagrass as influenced by trinexapac-ethyl. Journal of plant nutrition. **29**(2):273-282.

8. McCullough PE, Liu H, McCarty LB, Whitwell T, and Toler JE (2006) Bermudagrass putting green growth, color, and nutrient partitioning influenced by nitrogen and trinexapac-ethyl. Crop Science. **46**(4):1515-1525.

9. Brosnan JT, Thoms AW, Breeden GK, and Sorochan JC (2010) Effects of various plant growth regulators on the traffic tolerance of 'riviera'bermudagrass (cynodon dactylon l.). HortScience. **45**(6):966-970.

10. Williams DW, Burrus PB, and Cropper KL (2010) Seeded bermudagrass tolerance to simulated athletic field traffic as affected by cultivars and trinexapac-ethyl. HortTechnology. **20**(3):533-538.

11. McCarty LB and Miller G, Managing bermudagrass turf: Selection, construction, cultural practices, and pest management strategies. 2002: John Wiley & Sons.

12. Trenholm L, Dudeck A, Sartain J, and Cisar J (1998) Bermudagrass growth, total nonstructural carbohydrate concentration, and quality as influenced by nitrogen and potassium. Crop Science. **38**(1):168-174.

13. Carrow R, Johnson B, and Burns R (1987) Thatch and quality of tifway bermudagrass turf in relation to fertility and cultivation 1. Agronomy journal. **79**(3):524-530.

14. Beasley JS, Branham BE, and Spomer LA (2007) Plant growth regulators alter kentucky bluegrass canopy leaf area and carbon exchange. Crop science. **47**(2):757-764.

15. Fagerness MJ and Yelverton F (2000) Tissue production and quality of ‘tifway’bermudagrass as affected by seasonal application patterns of trinexapac-ethyl. Crop Science. **40**(2):493-497.

16. Kreuser WC and Soldat DJ (2011) A growing degree day model to schedule trinexapac-ethyl applications on agrostis stolonifera golf putting greens. Crop science. **51**(5):2228-2236.

17. Popovici CI (2013) Turfgrass management practices with impact in lowering lawn care maintenance costs. Metalurgia International. **18**(5):67.

18. Popovici CI (2013) Turfgrass management practices with impact in lowering lawn care maintenance costs. Metalurgia International. **18**(5):67-70.

19. Rowland J, Cisar J, Snyder G, Sartain J, and Wright A (2009) Effects of cultural practices on ultradwarf bermudagrass putting green surface properties. International Turfgrass Society Research Journal. **11**:203-2012.

20. Trappe JM, Richardson MD, and Patton AJ (2012) Species selection, pre-plant cultivation, and traffic affect overseeding establishment in bermudagrass turf. Agronomy Journal. **104**(4):1130-1135. https://doi.org/10.2134/agronj2011.0407

21. FIFA (2008) Fifa quality concept for artificial turf. Handbook of test methods.

CHAPTER III

EVALUATING ZOYSIAGRASS TRAFFIC TOLERANCE AND RECOVERY FOR SPORTS FIELD USE

3.1. Overview

Zoysiagrass (*Zoysia* spp.) is a warm-season turfgrass with low input and maintenance requirement. Previous studies have established the shade and wear tolerance of commercially available cultivars. However, the slow growth rate associated with zoysiagrass has limited its use on moderately trafficked sports fields. The objective of the study was to evaluate the traffic tolerance of come commercially available and experimental zoysiagrass cultivars compared to an industry standard hybrid bermudagrass cultivar under two traffic levels (moderate and high). The research was conducted in 2022 at two locations: TAMU Turfgrass Field Laboratory in College Station and Texas A&M AgriLife Research and Extension Center in Dallas, TX. The study design was a randomized complete block design (8x2 factorial) with four replications. The main plots were turfgrasses while the subplot were traffic levels (moderate: four passes weekly; high: eight passes weekly). Data were collected bi-weekly on turfgrass visual quality (1-9), turfgrass shear strength (Nm), surface hardness (Gmax), force reduction (%), and vertical deformation (mm). Among the zoysiagrasses evaluated, most of them demonstrated comparable performance to 'TifTuf' on the measured variables. However, one particular zoysiagrass experimental, 'DALZ 1818', showed promise in terms of visual quality and energy restitution. Despite these positive aspects, it exhibited less desirable surface characteristics compared to the other varieties. This study provides valuable information for identifying the zoysiagrass experimental varieties that warrant further evaluation and potential utilization on moderately trafficked sports fields.

3.2. Introduction

Zoysiagrass (*Zoysia* spp.) is a turfgrass species well-suited for use in transitional and warm climate regions. As of 2015, out of the 10,375 ha of zoysiagrasses planted in the United States, 95% were used on golf courses in the southeast and transition zone, likely because of its cold hardiness, wear tolerance, and slow growth rate [1-3]. Additional beneficial characteristics of zoysiagrass compared to other warm-season turfgrass species include overall higher quality, lower nutritional requirements, and increased tolerance to shade, drought, and salinity [3-9]. Although hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt Davy] is considered an industry standard for sports fields in warm climates, zoysiagrass could be another potential option because of comparable wear tolerance [10]; however, recovery from traffic on sports fields is concerning due to its slow growth rate [11].

Wear stresses are imposed on turfgrass sports fields because of trafficking activities from athletes or management equipment. Traffic induces wear (i.e., scuffing, tearing, and abrasion of shoot tissue) and soil compaction (i.e., the compression of soil particles), which can have a negative impact on turfgrass quality and field playability [12]. Many scientific publications on traffic studies in sports field research have focused on only bermudagrass cultivars, with minimal comparison to zoysiagrasses. One study that used zoysiagrass was conducted by Trappe et al. [10], where the traffic tolerance between five cultivars of bermudagrass and seven cultivars of zoysiagrass grown under full sun were evaluated. The authors reported that ‘El Toro,’ ‘Palisades,’ and ‘Zorro’ zoysiagrasses, as well as ‘Princess 77,’ ‘Riviera,’ ‘TifSport,’ and ‘Tifway’ bermudagrass, were statistically similar and had the highest turfgrass cover ratings (>72%) when trafficked under full sun. Nevertheless, the trafficking was limited to only four weeks during the study with a Cady traffic simulator, and only one traffic treatment level was used.

The lack of zoysiagrass traffic tolerance and recovery research for sports fields warrants further investigation, especially with the continued development of improved cultivars that have higher establishment and faster recovery rates [13, 14]. The objective of this study was to evaluate the traffic tolerance of several commercially available and experimental zoysiagrass cultivars compared to an industry standard hybrid bermudagrass cultivar under two traffic levels (moderate and high). It was hypothesized that the experimental zoysiagrasses would have better wear tolerance than the bermudagrass. It is hypothesized that the results from this study can provide sports fields managers with science-based recommendations about zoysiagrasses on sports fields.

3.3. Materials and Methods

Experimental design

The study was conducted in 2022 at two locations concurrently: the Texas A&M University Turfgrass Field Laboratory in College Station, TX and Texas A&M AgriLife Research and Extension Center in Dallas, TX. Trials at both locations were split-plot randomized complete block designs arranged as an 8x2 factorial with four replications. The main plots were zoysiagrasses with one hybrid bermudagrass cultivar for comparison, while the subplots were traffic levels (low and moderate). Both locations had native soil [A sandy loam in College Station (77% sand, 7% clay and 16% silt) and a Austin silty clay in Dallas (7% sand, 45% clay and 48% silt)] and plots were mowed at 12.7 mm twice a week. A slow-release 23-0-3 fertilizer was broadcasted to the plots before traffic treatments commenced and every four weeks during traffic at a rate of 48.8 kg N ha^{-1}. Irrigation was applied to prevent wilt and preemergence herbicide was applied to the plots prior to the study for weed control.

Turfgrass entries

Turfgrass entries included five zoysiagrass experimental cultivars from Texas A&M AgriLife Research (‘DALZ 1606,’ ‘DALZ 1905,’ ‘DALZ 1818,’ ‘DALZ 1713,’ and ‘TAES 6745-28’), two commercially available zoysiagrass cultivars (‘Palisades’ and ‘Zeon’), and one commercially available hybrid bermudagrass cultivar chosen as an industry standard (‘TifTuf’). Whole plots were 1.5 x 2.4 m with a 0.3 m border, while subplots were 1.5 x 1.2 m with a 0.3 m border.

Traffic treatments

Traffic treatments lasted for eight weeks from 7 Sept to 31 Oct 2022 and 31 Aug to 24 Oct 2022 at College Station and Dallas, respectively. A modified Baldree traffic simulator was used to apply traffic to the plots. The traffic simulator was a modified walk-behind aerification unit that had its tines replaced with cleated plates and springs to simulate foot traffic (Kowalewski et al., 2013). It was operated at a speed of 0.22 km hr^{-1} at each location. The moderate traffic plots received four total passes every week, which were divided into two passes (i.e., down and back) on Monday and Thursday. The high traffic plots received eight total passes every week, which were divided into four passes (i.e., down and back twice) on Monday and Thursday. Overall, the moderate and high trafficked plots received 32 and 64 passes of traffic by the end of the study 8-week study, respectively.

Data collection

Data were collected bi-weekly during trafficking on turfgrass visual quality, rotational turfgrass shear strength, energy restitution, vertical deformation, and surface hardness. Visual turfgrass quality ranged from 1-9, with 1 being dead turfgrass, 9 excellent quality, and 6 minimum acceptable quality [15]. Rotational turfgrass shear strength was collected with a Raw Traction Tester (Raw Stadia, Leicester, United Kingdom) and is a measure of how much rotational force it takes to tear the turfgrass. Energy restitution, vertical deformation, and surface hardness were measured using a Field Tester (Deltec Equipment, The Netherlands). The Field Tester device is equipped with an accelerometer and a 5 kg impact missile that is dropped from a height of 27.9 cm to the surface, guided through a cylindrical tube as it falls. Upon impact, the peak acceleration is extracted and used to compute values for the surface characteristics. One drop was made in each sub-plot. Energy restitution is a measure of the amount of energy returned from a surface upon impact of the surface [16]. It is measured relative to concrete, so units are percent. Vertical deformation is a measure of the depth to which a surface deforms upon impact by the tester in mm [16]. Surface hardness is the maximum acceleration relative to gravity experienced during impact on a surface (Gmax) [16]. Higher Gmax values indicate a harder surface.

Data analysis

Linear mixed models and repeated-measures ANOVA were applied to the data to assess differences among turfgrass. Statistical analyses were conducted in R Studio (v2023.03.0+386) using the ‘nlme,’ ‘stats,’ and ‘emmeans’ packages (RStudio, 2023). In cases where the model indicated a significant interaction between turfgrass and traffic level, the results for the interaction were reported. When appropriate, a Tukey’s HSD post hoc analysis was conducted for mean separation at a significance level of $P \leq 0.05$.

3.4. Results

Analysis of variance revealed a significant interaction between location and treatment for energy restitution and surface hardness. As a result, separate analyses were conducted for each location to examine these measurements. However, data from both locations were combined to analyze turfgrass cover, turfgrass shear strength, and vertical deformation.

Turfgrass measures

The effects of turfgrass and traffic on turfgrass quality were found to be significant (Table 3.1), yet they had no impact on turfgrass shear strength (Table 3.2). The turfgrass quality values for high traffic passes (4.7) were significantly lower than medium traffic passes (6.2). There was a significant interaction between traffic and date for turfgrass quality. Specifically, high traffic had significantly lower turfgrass quality than medium traffic passes for all dates except 0 week after traffic (WAT) (data not shown). The ’DALZ 1905’ cultivar had the lowest turfgrass quality (5.0) that was statistically similar to ‘Zeon’ (5.2), ‘DALZ 1713’ (5.4), ‘TAES 6745-28’ (5.6), and ‘DALZ 1606’ (5.6), but significantly lower than ‘TifTuf’ (5.6), ‘Palisades’ (5.7), and ‘DALZ 1818’ (5.7) (Fig. 5).

Soil measures

Traffic had a significant effect on vertical deformation (Table 3.1). The high traffic passes (9.9 mm) had a significantly lower vertical deformation than the low traffic passes (10.9 mm) (Table 3.3). For surface hardness and energy restitution, a significant interaction was observed between location and treatments. In College Station, traffic levels, turfgrass, and their interaction were all significant for surface hardness (Table 3.1). The softest surface was observed with the combination of TifTuf treatment with medium and high traffic, measuring 82.1 and 90.9 Gmax, respectively... These values were significantly lower than the combinations of medium traffic with DALZ 1905 (104.8 Gmax), high and DALZ 1606 (105.9 Gmax), high traffic with TAES 6745-28 (106.0 Gmax), and high traffic and DALZ 1818 (109.3 Gmax) (Table 3.2). None of the treatments had a significant effect on energy restitution.

In Dallas, both traffic and turfgrass had significant effects on surface hardness and energy restitution. High traffic passes (68.2 Gmax) resulted in a significantly lower surface hardness value compared to medium traffic passes (69.4 Gmax) (Table 3.3). Among the tested turfgrasses, TifTuf (67.8 Gmax) exhibited the softest surface, which was significantly lower than the surface hardness of DALZ 1818 (70.4 Gmax) (Fig. 7). For energy restitution, high traffic (15.6%) showed a significantly greater value than medium traffic (14.9%). Among the turfgrasses, TifTuf exhibited the highest energy restitution (16.2%), which was significantly higher than that of DALZ 1818 (14.1%) (Fig. 6).

3.5. Discussion

Both traffic and turfgrass had significant effects on measured surface characteristics. High traffic had a more negative impact on the visual quality of the turfgrasses compared to medium traffic. However, except for 'DALZ 1905,' all other experimental lines maintained similar visual quality to the industry standard turfgrass, TifTuf , regardless of the traffic level. Notably, 'DALZ 1818' and Palisades exhibited higher mean visual quality compared to TifTuf, although this difference was not statistically significant. These findings align with previous studies that reported the ability of zoysiagrass to withstand high levels of traffic stress [1, 10]. For example, in a study evaluating the visual turfgrass cover of bermudagrass and various zoysiagrass cultivars after subjecting them to four weeks of four traffic passes, researchers observed that the overall traffic tolerance of zoysiagrass was comparable to that of bermudagrass [10].

Generally, College Station had the hardest surface with a peak value of about 110 Gmax, while Dallas was at 71 Gmax. Soil type difference at the two locations could have influenced how the treatments affected surface characteristics, such as hardness and energy restitution. Despite the difference in traffic levels, TifTuf appeared to have a significant influence on the hardness of the surface. The combination of TifTuf and medium traffic pass resulted in a surface that was similar to its combination with high traffic pass, but significantly softer than the surfaces of zoysiagrass cultivars and experimental varieties. However, the combination of Palisades, Zeon, and two zoysiagrass experimental varieties ('DALZ 1818' and 'TAES 6745-28') with medium traffic pass resulted in surface hardness that was statistically similar to TifTuf combination with high traffic pass. Of these zoysiagrasses, all, except Zeon which is a dense, medium-fine textured, were coarse-textured. This confirms the result from a study where the traffic tolerance of seven zoysiagrass cultivars and five bermudagrass cultivars were examined under full sun for four weeks at four passes weekly. The zoysiagrasses that exhibited the highest coverage (>72%) were predominantly coarse-textured [10].

In Dallas, TifTuf also had the lowest mean surface hardness, although it was not significantly lower than the zoysiagrass varieties used in the study, except for 'DALZ 1818.' In both locations, 'DALZ 1818' consistently exhibited the hardest surface, regardless of its combination with traffic levels, probably because of its low dense growth compared to other cultivars. TifTuf is a hybrid bermudagrass recognized for its rapid thatch accumulation [16, 17]. This creates a soft layer beneath the grass, which aids in absorbing the impact force [18]. Surprisingly, the surface hardness value for high traffic was significantly lower than that of the medium traffic. This finding contradicts expectations and is in contrast to the measured energy restitution values, where high traffic expectedly led to a higher energy restitution upon impact compared to the medium traffic. This discrepancy between surface hardness and energy restitution values adds complexity to the interpretation of these results.

The present study collected data on field performance to measure the effect of traffic treatments and the selected turfgrasses. Similar studies only focused on the impact of treatments on visual cover and quality, and one of such studies was conducted by Trappe et al. [10]. In their study, ‘Cavalier,’ ‘Meyer,’ and ‘Palisades’ commercially available zoysiagrass cultivars maintained the highest turfgrass cover after four weeks of traffic but were statistically similar to the industry standard ‘Tifway’ hybrid bermudagrass used in the study. This was also observed in our study where ‘Palisades’ had statistically similar turfgrass quality, surface hardness , and energy restitution to TifTuf, and the zoysiagrass experimentals had similar performance to ‘Palisades’.

The two locations in this study reacted differently to traffic, likely due to the variation in soil type. College Station showed a higher susceptibility to the traffic than Dallas, particular with high traffic, where turfgrass cover reached zero in some of the zoysiagrass varieties by mid-study (data not reported). Therefore, traffic passes could be reduced depending on the soil type of the location where future studies are carried out. Furthermore, future studies could consider collecting recovery data during the study period and for several weeks following the conclusion of the traffic application. This would provide a more comprehensive understanding of the turfgrass's ability to recover from traffic stress over time.

3.6. Conclusion

This study confirmed previous reports regarding the high traffic tolerance of zoysigrass, as it demonstrated comparable performance to TifTuf under two different traffic regimes. Additionally, the variation in soil type between the two study locations did not significantly impact the visual quality of the turfgrass. However, there were notable differences in the measured surface characteristics, specifically surface hardness and energy restitution, across the locations. Among the zoysiagrass experimental lines, 'DALZ 1818' displayed the least desirable performance in terms of surface characteristics. By comparing these experimental lines with existing cultivars and TifTuf, our study provides valuable insights for selecting suitable turfgrass varieties for sports fields with moderate traffic. These findings offer guidance on which of the experimental lines show promise in terms of visual quality and energy restitution (‘DALZ 1818’) and should be considered for further evaluation and potential use in such settings.

Table 3.1. Analysis of variance (ANOVA) for the main effects of turfgrass, traffic, and date, as well as their interactions, on mean visual turfgrass quality, turfgrass shear strength, vertical deformation, energy restitution, and surface hardness.

	Visual Quality	**Shear**	**Vertical deformation**	**Energy restitution**		**Surface hardness**	
				College Station	**Dallas**	**College Station**	**Dallas**
Traffic (T)	***	NS	**	NS	**	***	**
Grass (G)	**	NS	NS	NS	***	***	*
Date (D)	***	*	***	***	***	***	***
T x G	NS	NS	NS	NS	NS	*	NS
T x D	***	NS	NS	NS	*	NS	NS
G x D	NS	NS	NS	NS	NS	*	NS
T x G x D	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS, not significant at $P \leq 0.05$

Table 3.2. Effects of turfgrass and traffic interaction on the mean surface hardness of zoysiagrasses and one hybrid bermudagrass in College Station.

Treatments	Surface Hardness
High + DALZ 1606	105.9 ± 3.8 c
High + DALZ 1713	100.9 ± 3.1 bc
High + DALZ 1818	109.3 ± 4.2 c
High + DALZ 1905	100.2 ± 3.5 bc
High + Palisades	102.2 ± 3.7 bc
High + TAES 6745-28	106.0 ± 3.8 c
High + TifTuf	91.0 ± 3.0 ab
High + Zeon	103.4 ± 3.3 bc
Low + DALZ 1606	98.7 ± 3.2 bc
Low + DALZ 1713	103.7 ± 3.7 bc
Low + DALZ 1818	97.4 ± 3.0 bc
Low + DALZ 1905	104.8 ± 3.4 c
Low + Palisades	98.4 ± 3.6 bc
Low + TAES 6745-28	97.0 ± 3.2 bc
Low + TifTuf	82.1 ± 1.9 a
Low + Zeon	96.7 ± 2.7 bc

Note: Means within a column with a common letter are not significantly different according to Tukey's HSD test (α = .05). High: eight traffic passes weekly; Moderate: four traffic passes weekly.

Table 3.3. Effects of turfgrass and traffic on mean energy restitution in College Station, energy restitution and surface hardness in Dallas, and vertical deformation from both locations.

Treatments	**Energy restitution (%) (College Station)**	**Energy restitution (%) (Dallas)**	**Surface hardness (Gmax) (Dallas)**	**Vertical deformation (mm)**
Traffic passes				
Low	17.0 ± 0.6	14.9 ± 0.2 a	69.4 ± 0.4 b	10.9 ± 0.3 b
High	18.3 ± 0.6	15.6 ± 0.2 b	68.2 ± 0.4 a	9.9 ± 0.3 a
Turfgrass				
DALZ 1606	17.5 ± 1.2	15.5 ± 0.3 b	68.2 ± 0.6 ab	9.6 ± 0.5
DALZ 1713	17.6 ± 1.2	15.3 ± 0.4 ab	68.6 ± 1.1 ab	10.7 ± 0.6
DALZ 1818	19.2 ± 1.4	14.1 ± 0.4 a	70.4 ± 0.6 b	11.7 ± 0.6
DALZ 1905	18.2 ± 1.1	15.5 ± 0.5 b	68.7 ± 0.8 ab	10.0 ± 0.5
Palisades	18.6 ± 1.2	15.3 ± 0.4 ab	69.0 ± 0.6 ab	9.9 ± 0.5
TAES 6745-28	17.9 ± 1.2	15.3 ± 0.4 ab	68.6 ± 0.8 ab	10.6 ± 0.5
TifTuf	14.5 ± 0.9	16.2 ± 0.4 b	67.8 ± 0.7 a	9.7 ± 0.4
Zeon	17.8 ± 1.0	15.1 ± 0.3 ab	69.2 ± 0.6 ab	10.8 ± 0.5

Note: Means within a column with a common letter are not significantly different according to Tukey's HSD test (α = .05). High: eight traffic passes weekly; Moderate: four low traffic passes weekly.

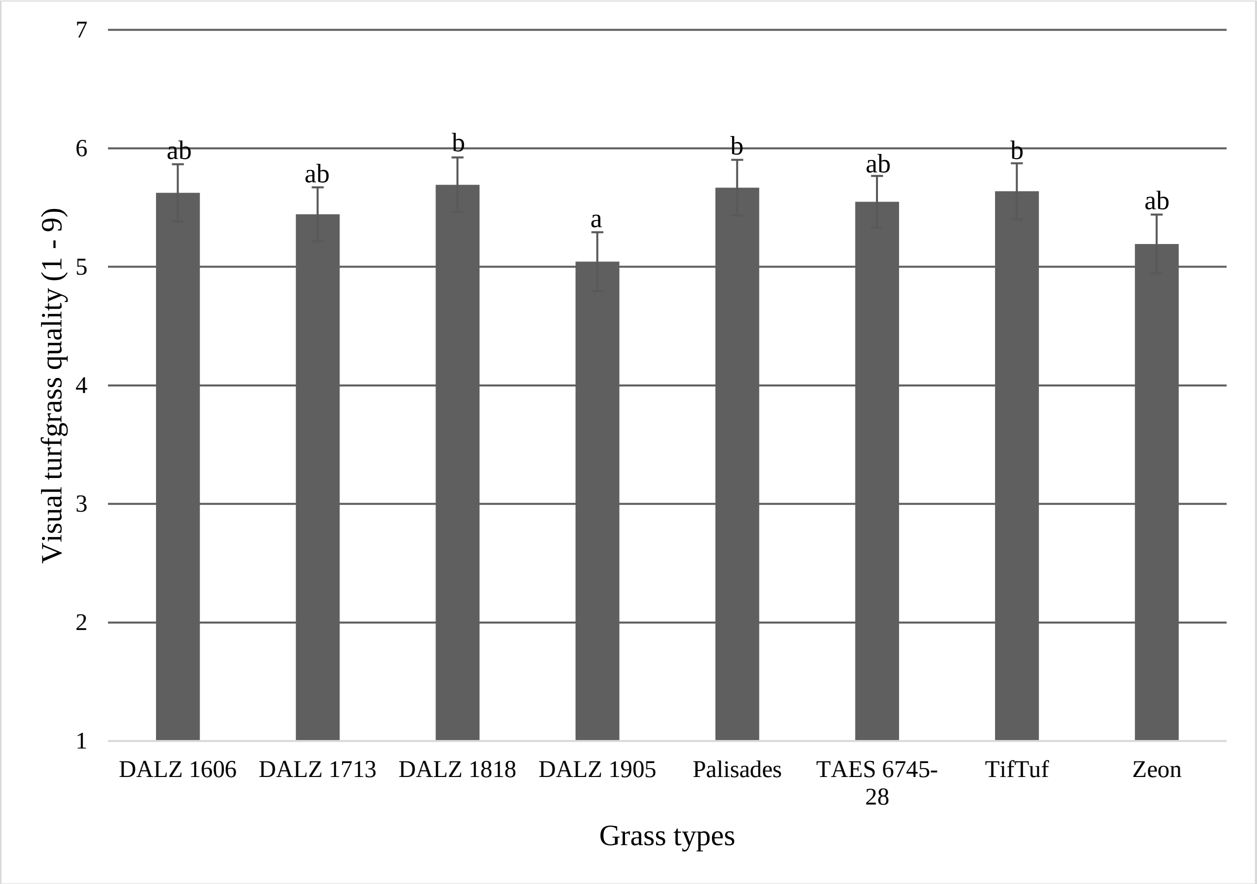

Figure 5: Effects of turfgrass on mean visual turfgrass quality. Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

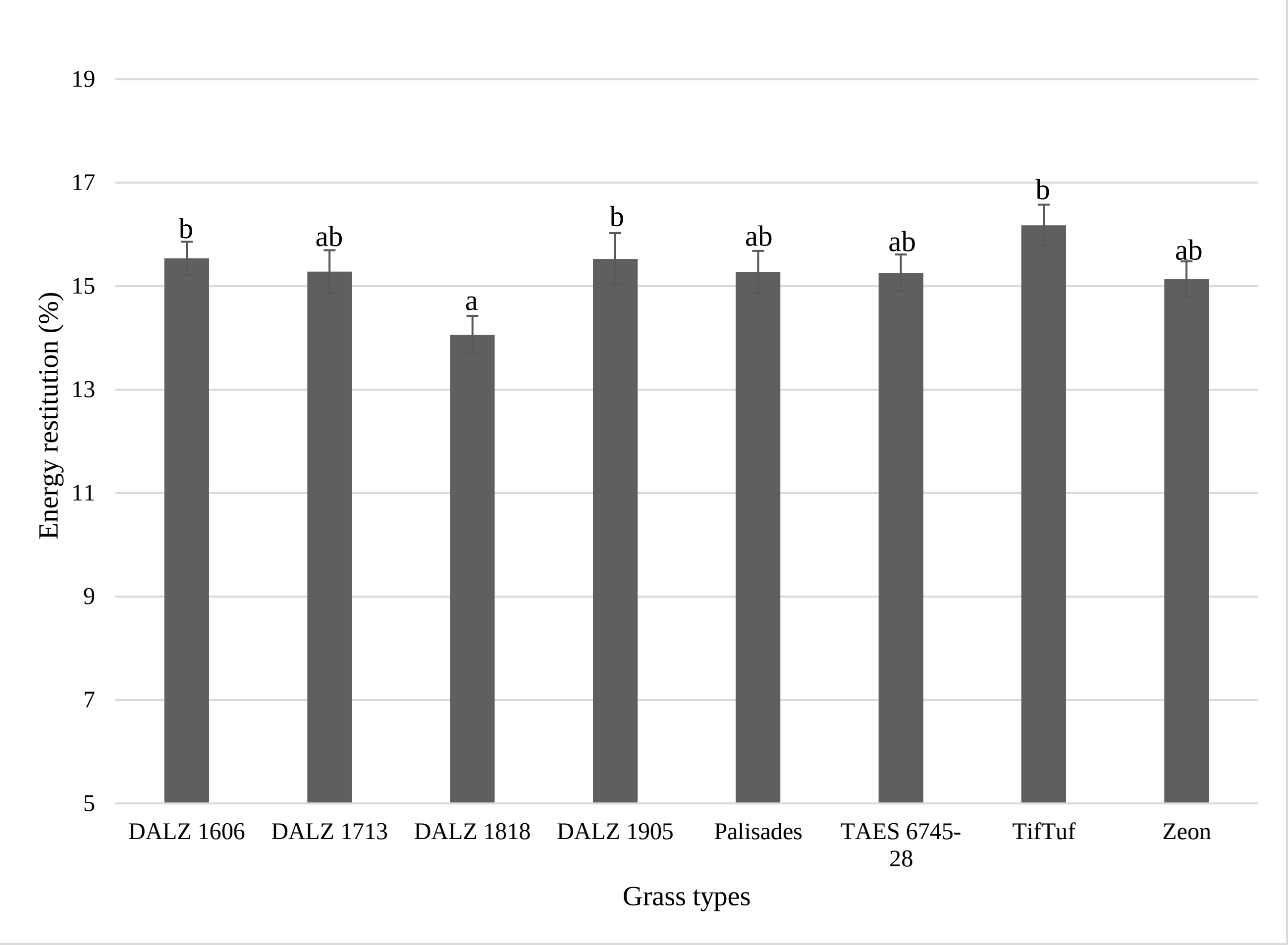

Figure 6: Effects of turfgrass on mean energy restitution (Dallas). Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

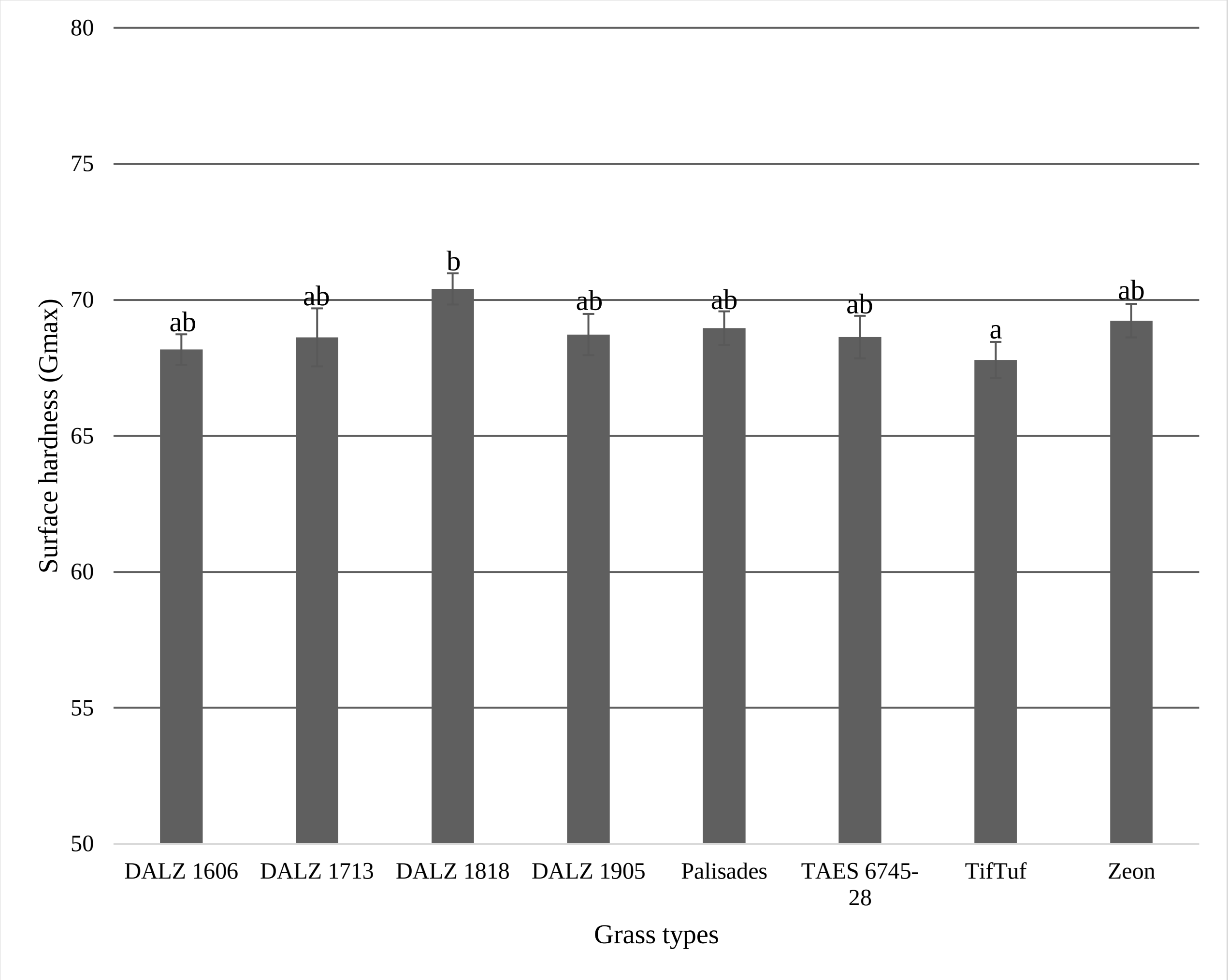

Figure 7: Effects of turfgrass on mean surface hardness (Dallas). Bars with a common letter are not significantly different according to Tukey’s HSD test (α = .05).

3.7. References

1. Lulli F, Volterrani M, Grossi N, Armeni R, Stefanini S, and Guglielminetti L (2012) Physiological and morphological factors influencing wear resistance and recovery in c3 and c4 turfgrass species. Functional Plant Biology. **39**(3):214-221.

2. Patton AJ and Reicher ZJ (2007) Zoysiagrass species and genotypes differ in their winter injury and freeze tolerance. Crop Science. **47**(4):1619-1627.

3. Patton AJ, Schwartz BM, and Kenworthy KE (2017) Zoysiagrass (zoysia spp.) history, utilization, and improvement in the united states: A review. Crop Science. **57**(S1):S-37-S-72.

4. Fry J, Kennelly M, and John RS (2008) Zoysiagrass: Economic and environmental sense in the transition zone. Golf Course Management. May:127-132.

5. Fuentealba MP, Zhang J, Kenworthy K, Erickson J, Kruse J, and Trenholm L (2016) Transpiration responses of warm-season turfgrass in relation to progressive soil drying. Scientia Horticulturae. **198**:249-253.

6. Marcum KB, Anderson SJ, and Engelke M (1998) Salt gland ion secretion: A salinity tolerance mechanism among five zoysiagrass species. Crop Science. **38**(3):806-810.

7. Patton AJ (2009) Selecting zoysiagrass cultivars: Turfgrass quality, growth, pest and environmental stress tolerance. Applied Turfgrass Science,(October):1019-01.

8. Trappe J and Patton A (2013) Evaluating two zoysiagrass cultivars in separate field trials for their preference of nitrogen source. Int. Turfgrass Res. J. **12**:575-580.

9. Wherley B, Skulkaew P, Chandra A, Genovesi A, and Engelke M (2011) Low-input performance of zoysiagrass (zoysia spp.) cultivars maintained under dense tree shade. HortScience. **46**(7):1033-1037.

10. Trappe JM, Karcher DE, Richardson MD, and Patton AJ (2011) Shade and traffic tolerance varies for bermudagrass and zoysiagrass cultivars. Crop science. **51**(2):870-877.

11. Turgeon AJ, Turfgrass management. 9th ed ed. 2012, Boston: Prentice Hall.

12. Trenholm L, Carrow R, and Duncan R (2000) Mechanisms of wear tolerance in seashore paspalum and bermudagrass. Crop science. **40**(5):1350-1357.

13. Chandra A, Milla-Lewis S, and Yu Q (2017) An overview of molecular advances in zoysiagrass. Crop Science. **57**(S1):S-73-S-81.

14. Okeyo DO, Fry JD, Bremer DJ, Chandra A, Genovesi D, and Engelke MC (2011) Stolon growth characteristics and establishment rates of zoysiagrass progeny. HortScience. **46**(1):113-117.

15. Morris KN and Shearman RC. Ntep turfgrass evaluation guidelines. in *NTEP turfgrass evaluation workshop, Beltsville, MD*. 1998.

16. McCarty LB, Willis TG, Toler JE, and Whitwell T (2011) ‘Tifeagle’bermudagrass response to plant growth regulators and mowing height. Agronomy Journal. **103**(4):988-994.

17. Trenholm L, Dudeck A, Sartain J, and Cisar J (1998) Bermudagrass growth, total nonstructural carbohydrate concentration, and quality as influenced by nitrogen and potassium. Crop Science. **38**(1):168-174.

18. Puhalla J, Krans J, and Goatley M, Sports fields: A manual for design, construction and maintenance. 1999: John Wiley & Sons.

CHAPTER IV

THE EFFECT OF TURFGRASS SPECIES AND MANAGEMENT PRACTICES ON SOCCER ATHLETES' PEAK TIBIAL ACCELERATIONS DURING ATHLETIC MANEUVERS

4.1. Overview

Athlete biomechanics can be influenced by the condition of a playing surface. They may be further impacted and complicated by the variability that exists between and within playing surfaces, especially natural turfgrass. The objective of this study was to utilize ankle-worn inertial measurement units (IMUs) to determine the effect of different turfgrass species, soil moisture levels, and mowing heights on peak tibial accelerations of collegiate soccer athletes. The study took place on three 5,000 ft^2 turfgrass research plots at the Texas A&M University Turfgrass Field Laboratory in College Station, TX in November 2022. Each of the plots had different fully established turfgrass species: hybrid bermudagrass ['Tahoma 31'], hybrid bermudagrass ['IronCutter'] overseeded with perennial ryegrass, or seashore paspalum ['Platinum TE']. Within each plot were four zones (100 x 8 ft) that consisted of a combination of "wet" (33-39% volumetric water content) or "dry" (23-29% volumetric water content) soil moisture levels and "high" (1.25") and "low" (5/8") mowing height. Participants were members of the Texas A&M University Men's and Women's Club Soccer teams. They were invited to the research location and equipped with the ankle IMUs on both feet and instructed to perform three different athletic maneuvers in each zone of a plot: a drop landing, drop jump, and modified acceleration-deceleration. The participants were asked afterwards to rate their perception about the visual appearance and firmness of each zone. The analysis of athletes' biomechanics, perception, and field performance testing data demonstrated that the dry-low zone emerged as the preferred option with the highest peak tibial acceleration. This study enhances our knowledge of how turfgrass species and management practices influence athlete-surface interactions, providing insights for selecting turfgrass species and making informed management decisions to optimize sports field conditions for athletes.

4.2.Introduction

Natural turfgrass sports fields undergo performance testing to meet the requirements set by sport governing bodies [1]. These tests aim to ensure that the surface characteristics of fields are safe, playable, and consistent [1, 2]. It is preferable to conduct these tests objectively to obtain replicable measurements [2, 3]. Several studies have investigated the influence of surface characteristics on athlete performance, perception, and injury risk [4-9]. However, surface characteristics tend to vary both spatially and temporally within and between fields [2, 10], making sports field management and athlete-surface interaction research complex and challenging [11].

Field construction, usage, and overall management are recognized as contributing factors to the observed variability in natural turfgrass sports fields [10]. While specific factors like turfgrass species, soil moisture, and mowing height have been reported to impact field characteristics, there is limited research directly comparing the influence of these factors on athletes, particularly in a real-world scenario [7, 9-10, 11]. However, advancements in wearable technology in team sports have opened up possibilities for quantifying athlete performance on different surfaces in-situ. For example, ankle-worn inertia measurement units (IMU) are non-invasive and capable of collecting impact data, such as peak tibial accelerations, from a surface during actual competition.

There is currently a lack of knowledge regarding the influence of fundamental sports field management decisions like turfgrass selection, irrigation practices, and mowing height on athletes’ peak tibial accelerations in the field. Additionally, there is limited research examining athletes’ perceptions of field condition variations resulting from these specific decisions. This information would be valuable for athletes and trainers in preparing for competitions on specific surfaces, as well as for sports field managers in making informed decisions to ensure that the field does not have a detrimental impact on athletes.

The objective of this study was to utilize ankle-worn IMUs and surveys to investigate the effect of turfgrass species, soil moisture, and mowing height on athletes’ peak tibial accelerations and perceptions during athletic maneuvers. The hypothesis is that the different turfgrass sports field conditions will influence athletes, potentially leading to implications for day-to-day field management and even larger (re)construction decisions.

4.3. Methods

Experimental design

The study was conducted in the fall of 2022 at the Texas A&M University Turfgrass Field Laboratory in College Station, TX. Three separate research plots were used to simulate sand-capped natural turfgrass sports fields. Each plot measured 15.2 x 30.5 m and was established from sprigs in the summer of 2021 at a rate of 15 bushels ha^{-1}. The turfgrasses included ‘IronCutter’ hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. x *Cynodon transvaalensis* Burtt Davy), ‘Platinum TE’ seashore paspalum (*Paspalum* vaginatum), and ‘Tahoma 31’ hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. x *Cynodon transvaalensis* Burtt Davy). By summer of 2022, all plots were fully established. On 14 Oct, the IronCutter plot was overseeded with perennial ryegrass (*Lolium perene*) at a rate of 244 kg ha^{-1} (Tri-Rye Grass Seed Blend, Mullica Hill, NJ) to have three distinct turfgrass species for the study.

The research was conducted from 15 to 29 Nov 2022 and was a 3x2x2 split-split-plot crossover design with three evaluation periods. Turfgrass species were considered whole plots, soil moisture conditions as sub-plots, and mowing heights as sub-sub plots. Each turfgrass species plot was divided into four equal strips measuring 2.4 x 30.5 m, representing the two additional treatment levels. Soil moisture included a “wet” [33-39% volumetric water content (VWC)] and “dry” (23-29% VWC) condition, whereas mowing height consisted of a “high” (3.1 cm) and “low” (1.6 cm) height of cut (Fig. 4.1).

Daily soil moisture readings were collected across the strips for twelve days prior to the study (28 Aug to 9 Sept, 2022) to better understand soil moisture conditions and assign the wet and dry soil moisture treatments. Mowing height treatments were assigned randomly to the wet and dry strips within each species and made using a walk-behind reel mower (Walk Greens Mower 180B, John Deere, Moline, IL) for the low height of cut and a push mower (TB160 Push Lawn Mower, Troy-Bilt, Cleveland, OH) for the high height of cut. A 50 cm wide buffer strip was made between sub-sub plots to ensure separation. Throughout the study period, the irrigation system was deactivated, and VWC levels were checked three times per day at a depth of 7.6 cm using a FieldScout TDR 350 Soil Moisture Meter (Spectrum Technologies, Inc., Plainfield, IL). If needed, VWC levels were manually raised by adding water to the strips using a 2.5 cm hose attached to a quick coupler. Three standby tarps were placed over the plots to prevent rain from falling directly on them during periods of rainfall.

Athletes

Participants were members of the Texas A&M University Men’s and Women’s Club Soccer teams. The average age, weight, and height of the men participants were 19.0 ± 1.9 years, 68.7 ± 6 kg, and 176.2 ± 4.4 cm, respectively, while women participants had an average age, weight, and height of 18.8 ± 0.8 years, 60.5 ± 8.8 kg, and 163.4 ± 4.5 cm, respectively. Approval was obtained from the Texas A&M University Institutional Review Board to conduct human subject research, and all the participants consented to the study. They were fitted with a non-invasive, ankle-worn IMU (Blue Trident IMU; Vicon Motion System, Denver, CO). The IMU had two accelerometers (±16 g at 1,125 Hz and ±200 g at 1,600 Hz), a gyroscope (±2,000 at 1125 Hz), and a magnetometer (±4,900 µT at 112 Hz). Peak tibial accelerations (i.e., loading force exerted on the lower leg during different activities) of the participants was the variable of interest. Athletes wore a standardized pair of soccer cleats (X Speedportal.3 FG; Adidas, Herzogenaurach, Germany) procured for the study to reduce the influence of variability induced by different footwear during the activities.

Athletic activities

Participants were scheduled based on their availability and invited multiple times to the facility to perform the tests on each species. They completed the study within a time frame ranging from one to three days. Those who completed the study in one day were provided with adequate rest periods between activities within species and between different species. Upon arrival, they were asked to do their usual warm-up activities, which consisted of knee pulls, build-up sprints, side shuffles, and walking ankle sweeps. Within each strip (wet-low, wet-high, dry-low, dry-high), the participants were asked to perform three different athletic activities:

1. Drop landing – participants stepped off a 40 cm high platform with their dominant foot and landed evenly on both feet.
2. Drop jump – participants stepped off a 40 cm high platform with their dominant foot and landed evenly on both feet, then jumped vertically as quickly as possible before landing on both feet again.

3. Modified acceleration–deceleration – participants were asked to accelerate 20 m at maximum effort before decelerating at maximum effort into a backpedal.

The athletic activities were replicated three times in each strip, and a 15-second rest period was provided between replications for drop landing and drop jumping. For the modified acceleration-deceleration exercise, a 90-second rest period was given between replications. To avoid fatigue during subsequent exercises, the four athletic activities were performed in the following order from least to most effort: drop step, drop jump, and modified acceleration-deceleration. Each study day involved the randomization of the order in which participants were transitioned from one zone to another within each species for the activities. Additionally, the assignment of the IMU sensors to the different species was randomized. The strips were color coded to ensure that only the researchers were aware of the specific conditions represented by each strip. These color codes were also utilized to guide the participants during the post-activity surveys. To ensure equal usage of the test plots and prevent excessive wear and soil compaction, the athletes were systematically directed to perform the athletic activities at various locations and in different directions within the strips.

Surface data other than VWC were collected at five locations within each strip before and after athletic activities on each study day. Data collected include normalized difference vegetation index (NDVI) using a RapidSCAN CS-45 (Holland Scientific Inc., Lincoln, NE), rotational turfgrass shear strength with a Raw Stadia Traction Tester (Raw Stadia, Leicester, United Kingdom), and energy restitution (i.e., energy returned from a surface), force reduction (i.e., shock absorption of a surface), vertical deformation (i.e., depth of penetration into a surface), and surface hardness using a Field Tester (Deltec Equipment, The Netherlands).

Data collection with inertial measurement units

The IMU software (Vicon Capture.U 1.3.1; Vicon Motion System, Denver, CO) installed on an iPad (Apple; Cupertino, California) was utilized to establish a Bluetooth connection with the ankle IMUs. Activity zones were created in the software to assist in data organization during collection. These activity zones were categorized based on turfgrass species and athletic activity for each participant. Three operators were assigned to the three whole plots, where the evaluation of up to three athletes took place simultaneously (i.e., one on each whole plot). An activity zone was initiated once a participant entered a specific strip within a particular turfgrass plot. To facilitate ease of exportation and subsequent data analysis, the data collected for a particular location and activity were timestamped.

At the conclusion of the evaluation period for a turfgrass species, participants were asked to complete a survey on the iPad hosted in Qualtrics (Provo, Utah, USA). The survey included several questions pertaining to their perception of each strip. For example, overall rate of exertion for the activities, perceived best area, perceived worst area, overall surface firmness, and visual appeal. Peak tibial acceleration (m/s^2) data were extracted from the ankle IMUs, and these data, along with survey responses, were subjected to analysis.

Data handling and analysis

Data from the IMUs were imported into PostgreSQL (Global Development Group) for further analysis. Prior to analysis, the data underwent a process of data cleaning to ensure accuracy and consistency. The accelerometer data was filtered using a fourth-order 50 Hz cutoff Butterworth filter, implemented through the SciPy Signal module in Python (v3.10). Subsequently, peak tibial accelerations were extracted for the different turfgrass species and zones using the 'find peaks' function in Python. This allowed for the identification of the maximum acceleration values for each specific combination of turfgrass species and zones. For data analysis, separate analyses of variance (ANOVA) were conducted for male and female athletes using R Studio (v2023.03.0+386). The statistical packages 'nlme,' 'stats,' and 'emmeans' were employed for these analyses. In cases where significant main effects were observed, post hoc analysis using Tukey's HSD test was performed to compare the means. The significance level for these comparisons was set at $P \leq 0.05$, indicating the threshold for statistical significance.

4.4. Results

Throughout the study, field conditions were monitored by collecting data on various soil measures, including surface hardness, force reduction, vertical deformation, energy restitution, and volumetric water content. Additionally, we assessed turfgrass measures such as shear strength and NDVI. This data collection allowed us to observe the consistent performance of the fields during activities throughout the duration of the study.

Drop step activity

A significant impact on peak tibial accelerations between zones was experienced by both male and female athletes during the drop step activity. Among male athletes, the wet-high zone demonstrated the lowest peak tibial acceleration (172.9 m/s^2) (Fig. 10). This value was statistically similar to the peak tibial acceleration observed in the wet-low zone (186.1 m/s^2). However, both values were significantly lower than the peak tibial accelerations recorded in the dry-high zone (197.7 m/s^2) and the dry-low zone (196.7 m/s^2) (Fig. 10). Similarly, among female athletes, the peak tibial accelerations observed in the wet-high zone (156.93 m/s^2), wet-low zone (163.8 m/s^2), and dry-high zone (166.9 m/s^2) were comparable (Fig. 13). However, the peak tibial acceleration recorded in the dry-low zone (185.3 m/s^2) was found to be significantly higher than that of the two wet zones (Fig. 13).

Drop jump activity

Both the turfgrass species and zone factors had a significant impact on the first and second drop jump measurements of male athletes. However, no significant effect was observed on the peak tibial acceleration of female athletes (Table 4.1). During the first drop jump activity, peak tibial accelerations in the dry zones did not show any significant differences, although the dry-low zone recorded the highest value (195.5 m/s^2) (Fig. 11). The dry-high zone, with a peak tibial acceleration of 176.7 m/s^2, did not exhibit a significant difference compared to the wet zones (Fig. 11). Similarly, the second jump activity displayed a similar pattern to the first drop jump where wet zones consistently demonstrated the lowest peak tibial acceleration (Fig. 12).

Modified acceleration-deceleration activity

Zone and turfgrass species had no significant effect on the peak tibial accelerations of the male athletes during the modified acceleration-deceleration activity, but turfgrass species effect on female peak tibial acceleration was significant (Table 4.1). The peak tibial acceleration of the female athletes on hybrid bermudagrass (287.5 m/s^2) was significantly lower than overseeded hybrid bermudagrass (320.6 m/s^2) and seashore paspalum (321.4 m/s^2) (Fig. 9).

Athletes' perception

The average rate of perceived exertion (RPE) was statistically similar between overseeded hybrid bermudagrass (10.61 ± 0.51), hybrid bermudagrass (10.94 ± 0.64), and seashore paspalum 10.79 ± 0.50. In the survey question on RPE, the value ranged from 6 (no exertion) to 20 (maximum exertion). Perceived best and worst field conditions varied between species (Fig. 14; Fig. 15). On overseeded hybrid bermudagrass, they preferred the wet-low strip because of it was a good balance between hard and soft (Fig. 14 A), and the same wet-low strip was perceived to be the worst by the other mejority because it was too soft (Fig. 15 A). The low height zones (wet-low and dry-low) were perceived to be the best on seashore paspalum because of its firmness (Fig. 14 B), and wet-low was perceived as the worst because it was too stiff (Fig. 15 B). This result was different on hybrid bermudagrass where the athletes perceived the dry-high as the best zone because of its firmness (Fig. 14 C), and wet-low as the worst because it was too wet and thin (Fig. 15 C).

Athlete perception of visual appeal varied between turfgrass species, but their perception on firmness was uniform across turfgrass species. The dry-low, wet-low, and dry-high strips were rated higher visually than the wet-high strip for overseeded hybrid bermudagrass (8.4), seashore paspalum (8.2), and hybrid bermudagrass (7.0), respectively (Fig. 16). On all the turfgrass species used for the study, the athletes perceived the dry-low zone to be the firmest (Fig. 17).

4.5. Discussion

The peak tibial acceleration experienced by the athletes varied across different zones and turfgrass species, depending on the specific activity being performed. Notably, this variation was also observed between male and female athletes, except for the drop step activity where the management practices had a significant impact on the peak tibial acceleration for both genders. During the drop step activity, male athletes exhibited the highest peak tibial acceleration in the dry zones, regardless of the mowing height (dry-high and dry-low). This trend was similar for female athletes as well, with the exception that the peak tibial acceleration in the dry-high zone was not statistically different from that in the wet zones. This observation suggests that the softer wet strips may result in increased energy demands from players and absorb a significant amount of the energy that should be returned to the athletes [12]. Therefore, this contributes to a lower peak tibial acceleration compared to the dry zones. Our finding aligns with other biomechanical research that report the hardest surface restituting the highest energy. However, this differed from what Stiles et al. [12] observed where the peak rate of loading of the participants were significantly higher for the soft surface (wet) compared to the hard surface (dry). Their study was conducted in a laboratory and could be responsible for the observed differences.

Significant effects of the management practices on the peak tibial acceleration of male athletes were observed during the first and second drop jump activities. Consistent with the findings in other activities, it was evident that the dry zones exhibited the highest peak tibial acceleration, regardless of the mowing heights. However, among the dry zones, only the dry-low zone showed a statistically significant increase in peak tibial acceleration compared to the wet zones. These findings provide further confirmation that wet surfaces have a higher capacity for energy absorption and subsequently return less energy to the athletes during physical activities [13]. This behavior can be attributed to the softening of the surface due to moisture, allowing it to effectively dissipate and dampen the energy generated by the athletes. Furthermore, the high cut stripts, characterized by a greater amount of verdure (vegetative growth), also contribute to energy absorption. The presence of more vegetation on the surface allows for additional energy to be absorbed, further enhancing the force reduction capacity of the turfgrass. Grossi et al. [14] also observed this in their study where the lowest mowing (height) resulted in the hardest surface and significantly increasing ball rebound as a result of the reduced force reduction.

During the modified acceleration-deceleration activity, the behavior was consistent across different zones and turfgrass species for male athletes. However, notable differences were observed in the peak tibial acceleration of female athletes on hybrid bermudagrass compared to seashore paspalum and overseeded hybrid bermudagrass. Among the three species examined in the study, hybrid bermudagrass exhibited the softest surface, primarily due to the presence of a high accumulated thatch layer. Consequently, this surface could absorb a greater amount of impact energy [15]. This absorption of energy likely contributed to the lower tibial acceleration experienced by female athletes on hybrid bermudagrass. It is hypothesized that the turfgrass species did not have a significant impact on male athletes during this activity due to their relatively heavier weights compared to the female athletes. The male athletes were able to generate more force, which in turn was effectively returned during the activity, potentially offsetting any variation in surface properties among the turfgrass species.

The survey response data collected from athletes revealed a consistent preference for the dry zone with a low mowing height. This preference aligns with the performance outcomes observed during the drop step and drop jump activities in different zones. The athletes demonstrated superior performance in the dry-low zone compared to the other management practices, indicating a relationship between their preferred surface choice and actual performance. This finding further supports the notion that athletes perceive firm surfaces, particularly the dry-low zone in this study, as being optimal for their gameplay.

To the best of the authors' knowledge, this study represents the first attempt to investigate the combined impact of turfgrass species, mowing height, and soil moisture on athlete biomechanics and perceptions in the field using wearables. Moving forward, there is great potential for future research to expand upon these findings by collecting data during real competition under various field scenarios. However, it should be noted that such studies may encounter challenges in effectively controlling the inherent within-field variability of surface characteristics, which could complicate data interpretation.

Furthermore, there is an opportunity for additional research to explore how these specific field conditions interact with factors such as ball roll and bounce and shoe design. Understanding the holistic interactions between surfaces, athletes, balls, and shoes under these a variety of surface conditions would provide a comprehensive perspective on how they collectively influence athletes. By expanding the investigation to encompass the broader context of game scenarios and considering the interplay of various elements, researchers can gain deeper insights into the complex dynamics and impact of surface interactions on athlete and performance.

4.6. Conclusion

This study sheds light on the variability in peak tibial acceleration experienced by athletes across different natural turfgrass sports field characteristics during various activities. The findings showed that all athletes exhibited higher peak tibial acceleration in the drier conditions, while female athletes showed lower acceleration on Tahoma 31 hybrid bermudagrass. The preference of the athletes for firm surface aligns with their better performance on the dry-low zones and field performance testing data. The study also identifies the significance of mowing heights and soil moisture levels in energy absorption and force reduction capacity of the turfgrass. Ultimately, this research contributes to a more comprehensive understanding of how field conditions influence athlete biomechanics and perceptions, and validates field tests, such as surface hardness/firmness with player perceptions, which can inform surface design and maintenance practices to enhance athlete safety and performance.

Table 4.1. Effect of turfgrass species and management practices on the peak tibial acceleration of male and female athletes' during modified acceleration-deceleration, drop step, and drop jump activities.

	Drop step		**First drop jump**		**Second drop jump**		**Modified acceleration-deceleration**	
	Male	Female	Male	Female	Male	Female	Male	Female
Management practices (M)	*	*	*	NS	*	NS	NS	NS
Turfgrass species (T)	NS	NS	*	NS	*	NS	NS	*
T x M	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
NS, not significant at P ≤ 0.05

Figure 8. Plot layout example showing IronCutter hybrid bermudagrass overseeded with perennial ryegrass. Light blue strip, wet-high; navy blue strip, wet-low; white, dry-high; orange, dry-low.

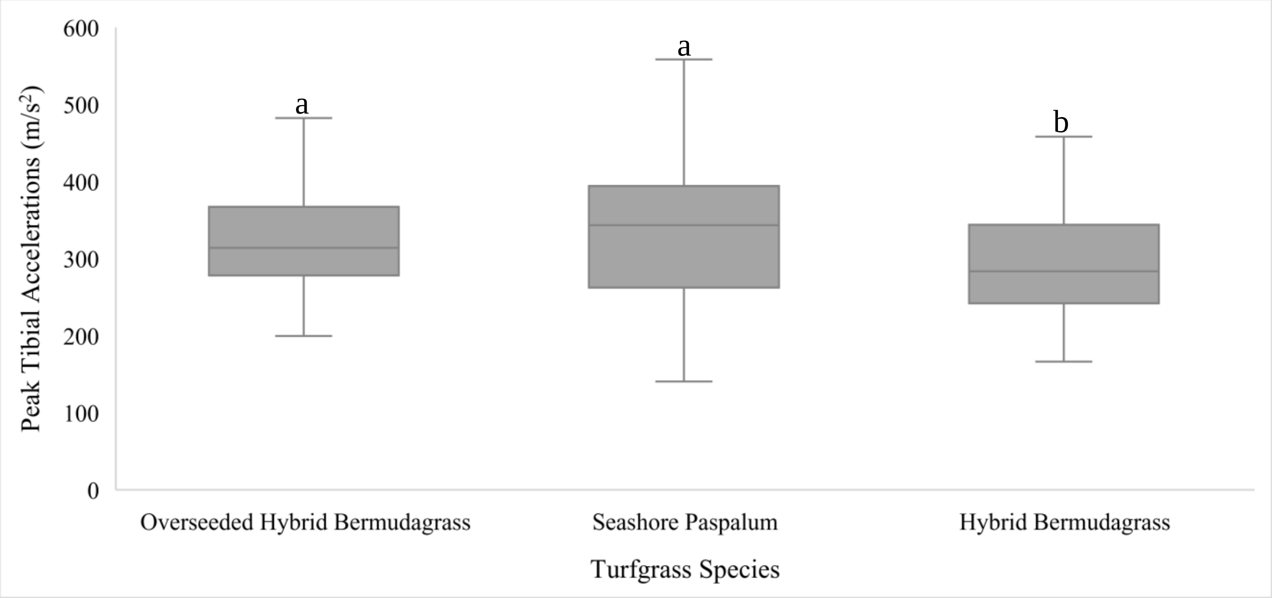

Figure 9. Box and whisker plots for peak tibial accelerations (m/s^2) within the grass species during the modified acceleration-deceleration activity by the collegiate female club soccer athletes. The line in a box and its whiskers represent the median and standard deviation, respectively. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

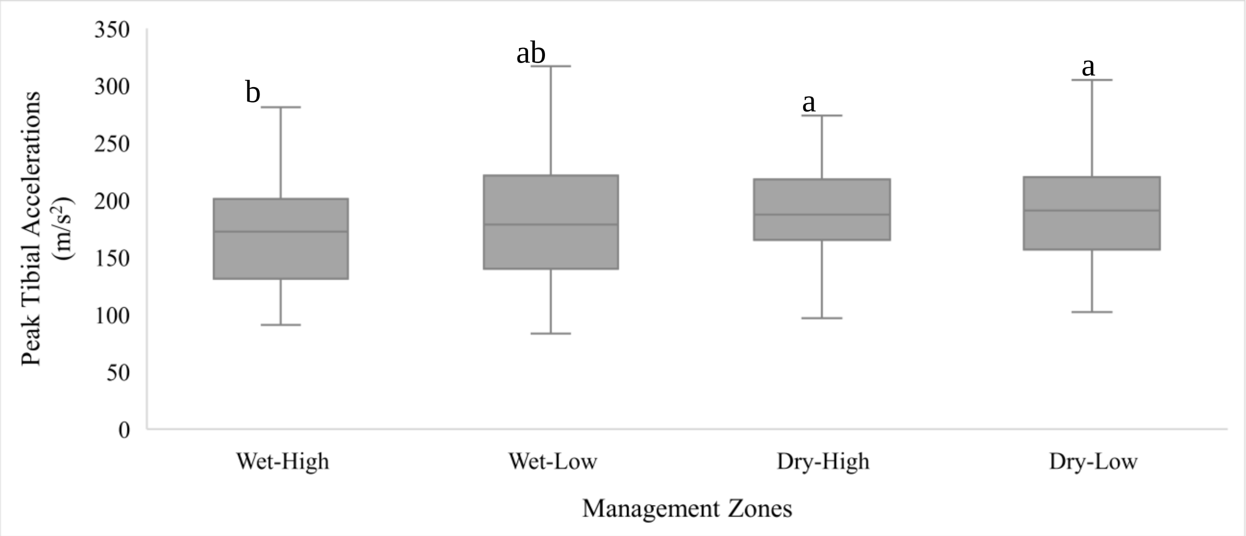

Figure 10. Box and whisker plots for peak tibial accelerations (m/s^2) within management zones during the drop step activity by the collegiate male club soccer athletes. The lines in the box and whiskers represent the median and standard deviation, respectively. Bars with a common letter are not significantly different according to Tukey's HSD test ($\alpha = .05$).

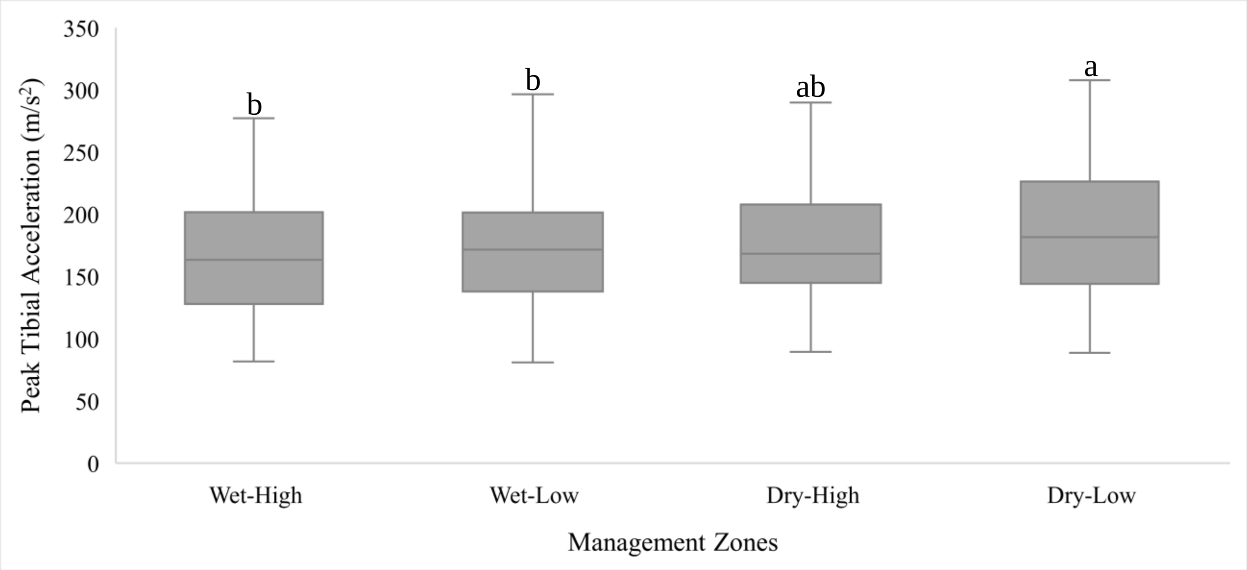

Figure 11. Box and whisker plots for peak tibial accelerations (m/s^2) within management zones during the first landing of the drop jump activity by the collegiate male club soccer athletes. The lines in the box and whiskers represent the median and standard deviation, respectively. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

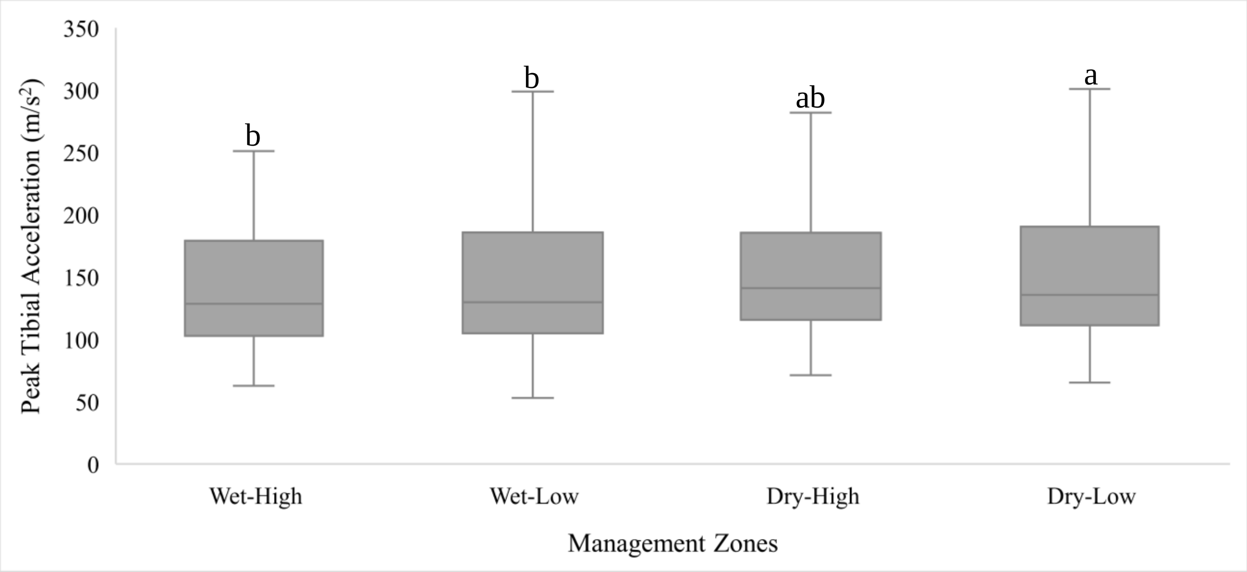

Figure 12. Box and whisker plots for peak tibial accelerations (m/s^2) within management zones during the second landing of the drop jump activity by the collegiate male club soccer athletes. The lines in the box and whiskers represent the median and standard deviation, respectively. Bars with a common letter are not significantly different according to Tukey's HSD test ($\alpha = .05$).

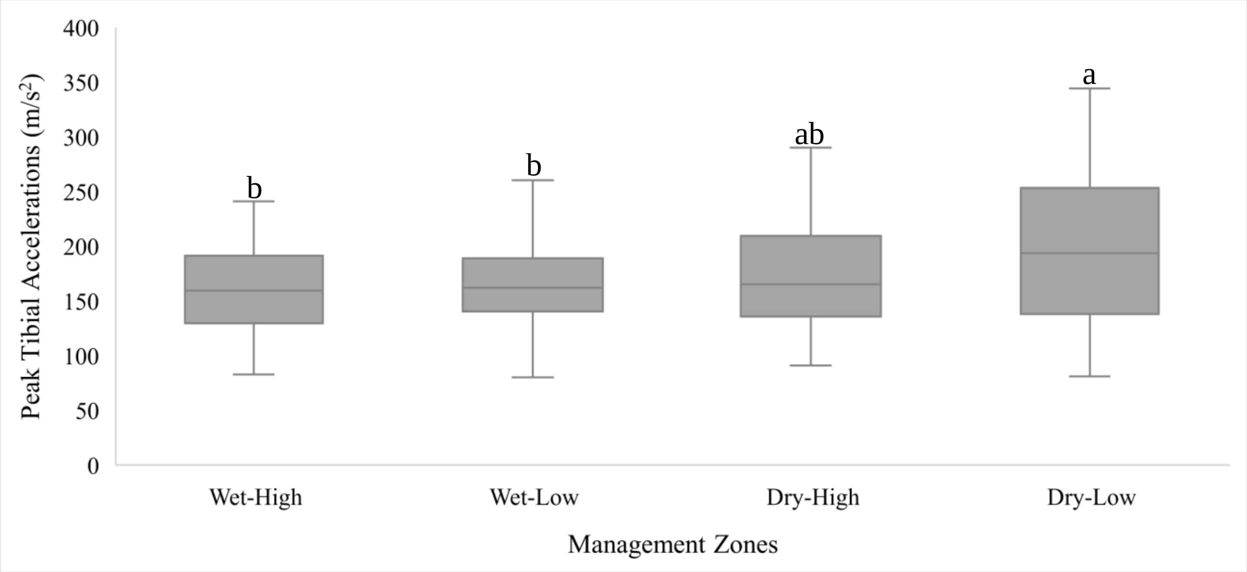

Figure 13. Box and whisker plots for peak tibial accelerations (m/s^2) within management zones during the drop step activity by the collegiate female club soccer athletes. The lines in the box and whiskers represent the median and standard deviation, respectively. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

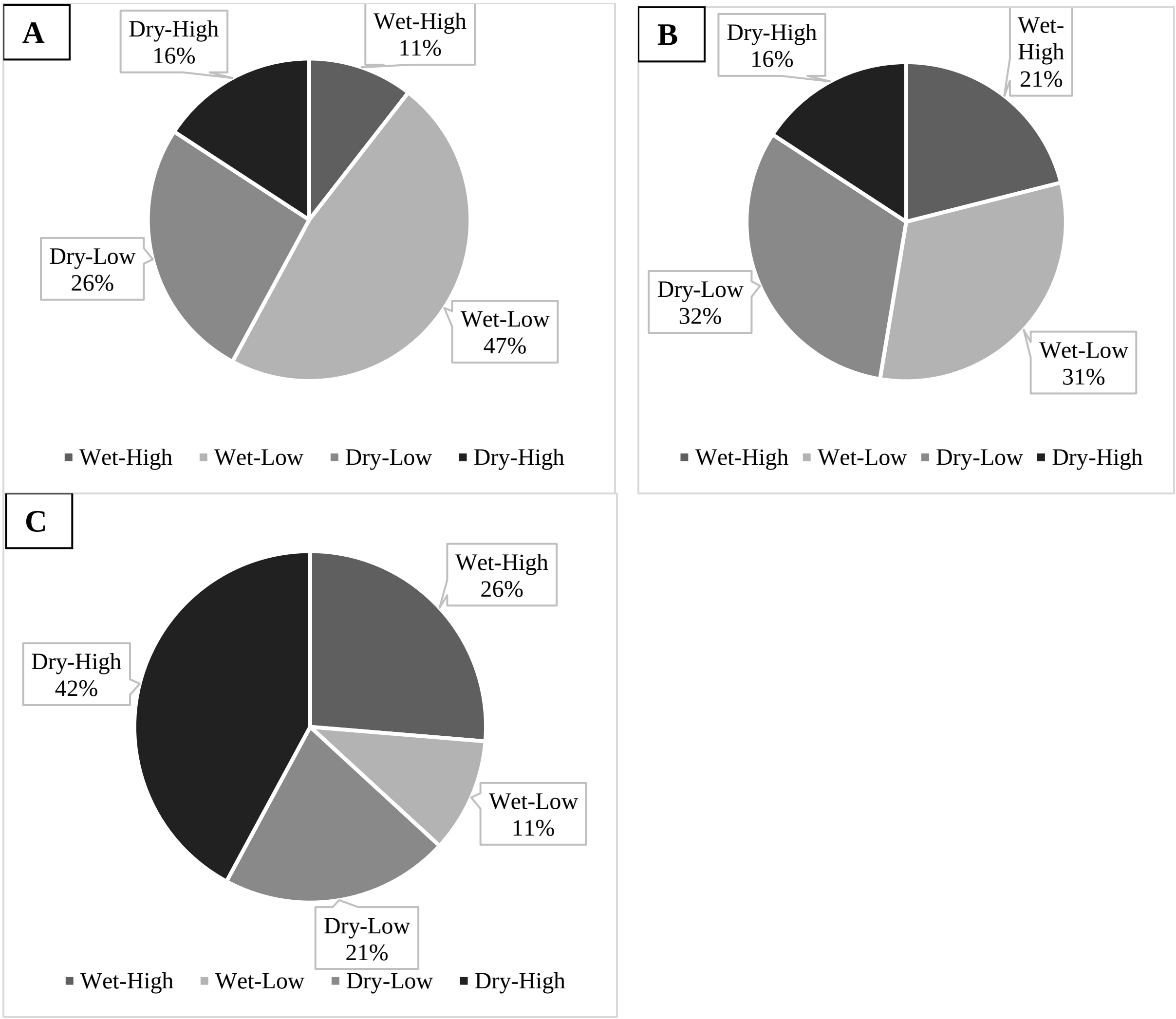

Figure 14. Athletes' perception of the best zone within A: Overseeded hybrid bermudagrass; B: Seashore paspalum; C: Hybrid bermudagrass.

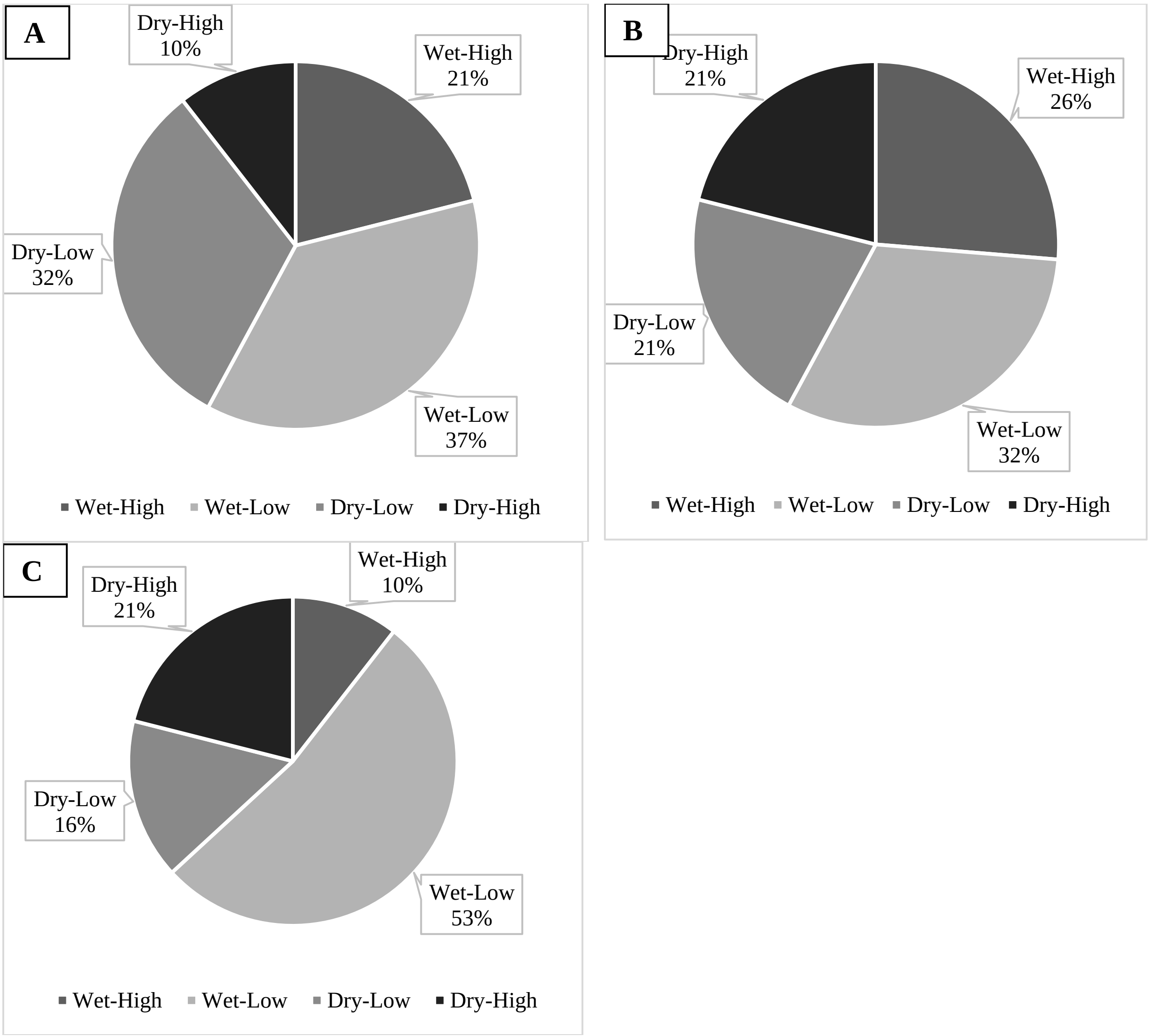

Figure 15. Athletes' perception on the worst zone within each turfgrass. A: Overseeded hybrid bermudagrass; B: Seashore paspalum; C: Hybrid bermudagrass.

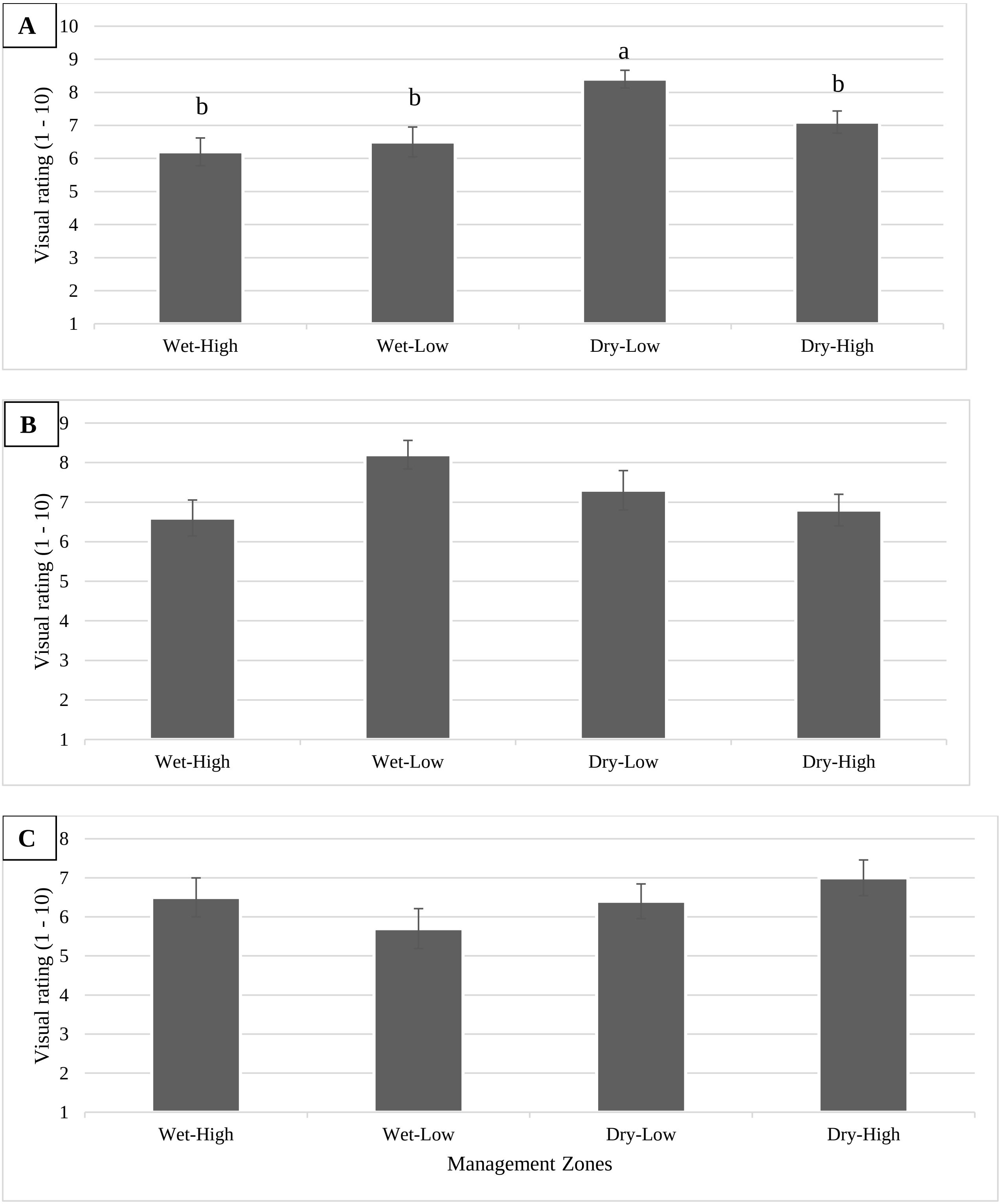

Figure 16. Athletes' perception on the visual appeal of the management zones within each turfgrass. A: Overseeded hybrid bermudagrass; B: Seashore paspalum; C: Hybrid bermudagrass. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

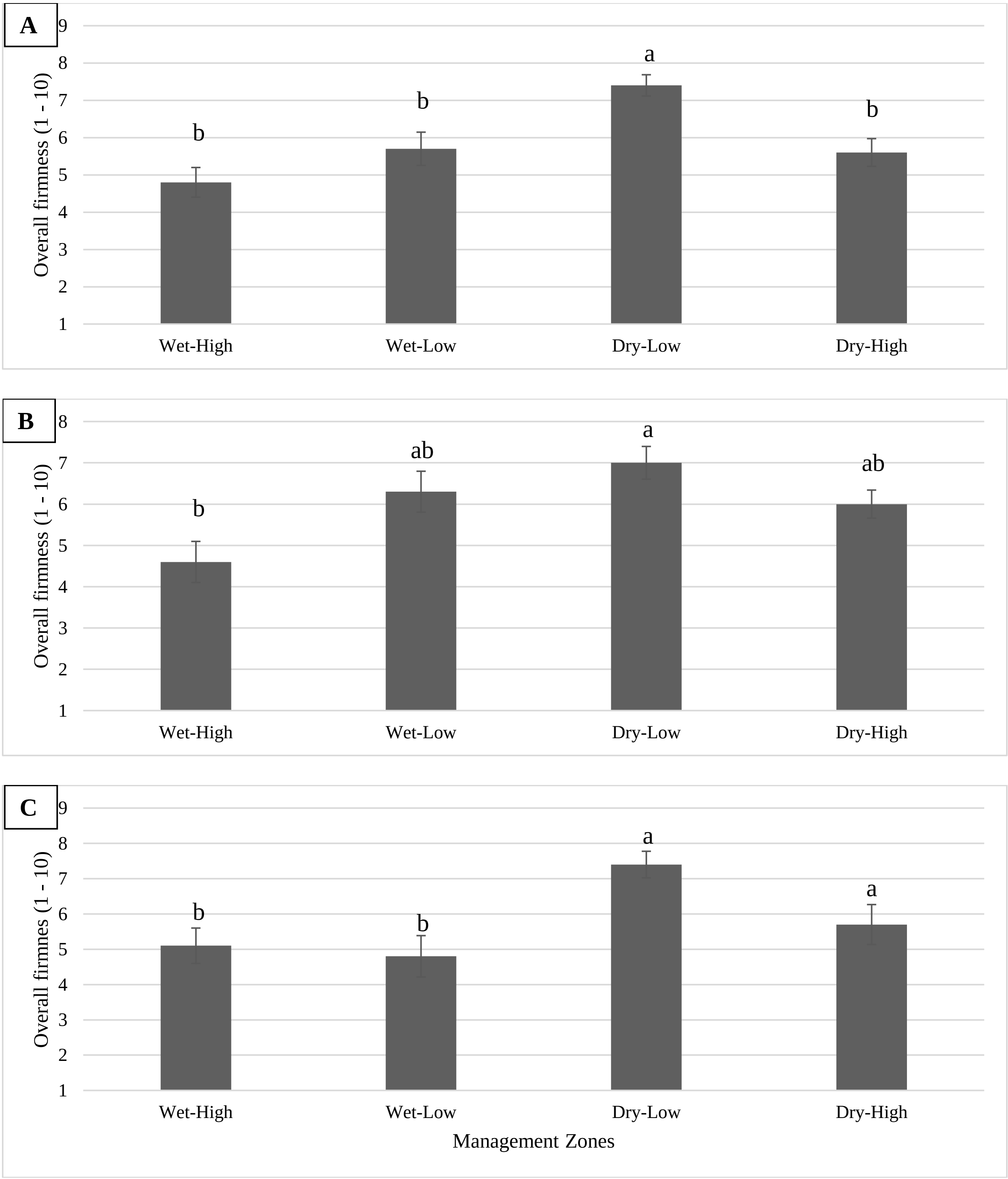

Figure 17. Athletes' perception on the firmness of the zones within each turfgrass. A: Overseeded hybrid bermudagrass; B: Seashore paspalum; C: Hybrid bermudagrass. Bars with a common letter are not significantly different according to Tukey's HSD test (α = .05).

4.7. References

1. FIFA (2008) Fifa quality concept for artificial turf. Handbook of test methods.

2. Bartlett M, James I, Ford M, and Jennings-Temple M (2009) Testing natural turf sports surfaces: The value of performance quality standards. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. **223**(1):21-29. https://doi.org/10.1243/17543371JSET24

3. McAuliffe KW. The role of performance testing and standards in the sports turf industry: A case study approach. in *II International Conference on Turfgrass Science and Management for Sports Fields 783*. 2007. doi.org/10.17660/ActaHortic.2008.783.41

4. Fuller CW, Dick RW, Corlette J, and Schmalz R (2007) Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 2: Training injuries. British journal of sports medicine. **41**(suppl 1):i27-i32.

5. Martinez A, Dura J, Gamez J, Rosa D, Zamora T, and Alcantara E. Artificial and natural turf: Biomechanical differences between surfaces. in *Communications of the Fifth World Congress on Science and Football. J Sports Sci*. 2004.

6. Meyers MC and Barnhill BS (2004) Incidence, causes, and severity of high school football injuries on fieldturf versus natural grass: A 5-year prospective study. The American journal of sports medicine. **32**(7):1626-1638.

7. Burbrink CM and Straw CM (2023) Spatiotemporal variability of a stadium football pitch during a professional tournament. Sports Engineering. **26**(1):8. https://doi.org/10.1007/s12283-023-00399-4

8. Straw CM, Carrow R, Bowling W, Tucker K, and Henry G (2018) Uniformity and spatial variability of soil moisture and irrigation distribution on natural turfgrass sports fields. Journal of Soil and Water Conservation. **73**(5):577-586.

9. Straw CM, Henry GM, Shannon J, and Thompson JJ (2019) Athletes' perceptions of within-field variability on natural turfgrass sports fields. Precision Agriculture. **20**:118-137.

10. Straw CM, Principe FM, Kurtz EL, Wiese-Bjornstal DM, and Horgan BP (2020) Within-field variability of turfgrass surface properties and athlete performance: Modeling their relationship using gps and gis technologies. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. **234**(2):170-175.

11. Baker S (1991) Temporal variation of selected mechanical properties of natural turf football pitches. Journal of the Sports Turf Research Institute.

12. Stiles VH, Guisasola IN, James IT, and Dixon SJ (2011) Biomechanical response to changes in natural turf during running and turning. Journal of applied biomechanics. **27**(1):54-63. https://doi.org/10.1123/jab.27.1.54

13. Guisasola I, James I, Llewellyn C, Bartlett M, Stiles V, and Dixon S (2009) Human–surface interactions: An integrated study. International Turfgrass Society Research Journal. **11**:1097-1106.

14. Grossi N, Volterrani M, Magni S, and Miele S. Tall fescue turf quality and soccer playing characteristics as affected by mowing height. in *I International Conference on Turfgrass Management and Science for Sports Fields 661*. 2003. https://doi.org/10.17660/ActaHortic.2004.661.41

15. Puhalla J, Krans J, and Goatley M, Sports fields: A manual for design, construction and maintenance. 1999: John Wiley & Sons.

CHAPTER V

CONCLUSIONS

The influence of natural turfgrass sports field characteristics and management strategies on field quality, playability, and athletes' performance is evident. However, there is a lack of comprehensive studies addressing the concerns of sports field managers regarding the impact of these activities on athletes. The purpose of the studies conducted in this thesis was to bridge this knowledge gap and provide sports field managers with information on construction and management practices for natural turfgrass sports fields that prioritize safety and playability.

Chapter II of the thesis investigated the impact of different PGR application strategies and reapplication intervals, as well as cultivation practices for density management in hybrid bermudagrass sports fields. The study examined various turfgrass and soil measures, including NDVI, turfgrass cover, shear strength, surface hardness, force reduction, energy restitution, and vertical deformation. Two simulated American football field conditions, representing high school and collegiate scenarios, were considered. The results showed that PGR application had minimal effect on the turfgrass measures in the high school field scenario, but it did have an impact on the collegiate field scenario. It was found that continuous application of PGR at the full rate during traffic showed no significant advantage compared to split rate application and stopping before traffic. This suggests that sports fields can achieve comparable results while saving costs by implementing split rate application and discontinuing PGR during traffic. Furthermore, the study found that the rake treatment was less damaging to turfgrass quality compared to verticutting and verticutting + raking treatments. The rake treatment also proved to be less time-consuming, resulting in savings on labor costs compared to the other two treatments.

Chapter III of the thesis examined zoysiagrasses as potential alternatives to the industry-standard hybrid bermudagrass 'TifTuf' for moderately trafficked sports fields. The study aimed to identify zoysiagrass entries that could perform comparably to 'TifTuf.' Among all the zoysiagrass entries examined, 'DALZ 1818' exhibited good visual quality and energy restitution compared to the bermudagrass after traffic. This suggests that 'DALZ 1818' has potential and should be further evaluated in future breeding research.

Chapter IV investigated the effect of turfgrass species (overseeded hybrid bermudagrass, seashore paspalum, and hybrid bermudagrass), soil moisture (dry: 23-29%; wet: 33-39%), and mowing heights (low: 1.6 cm; high: 3.1 cm) on athletes’ peak tibial accelerations and their perceptions during athletic activities (drop landing, drop jump, and modified acceleration-deceleration). Athletes exhibited significantly higher peak tibial accelerations on dry-low management zones compared to wet management zones, indicating a consistent trend across all three turfgrass species. Athletes’ biomechanics aligned with their perceptions about the zones, as they perceived dry-low zone to be the firmest and most preferred. This shows that athletes’ perceptions can be a key factor that can be incorporated into surface design and maintenance practices.

The findings of these studies demonstrate the significant influence of field conditions on athlete biomechanics and perception. They also provide insights into the application rate and reapplication strategy of PGR, as well as density management on natural turfgrass sports fields. Furthermore, these studies identify several areas for future research, including the evaluation of zoysiagrass as an alternative to hybrid bermudagrass on moderately trafficked sports fields, the incorporation of cultivation practices such as aerification and topdressing into sports field management, and the expansion of athlete-surface interaction studies to include factors like cultivation practices, ball- and shoe-surface interaction. The overarching goal of this research was to contribute to the knowledge of sports field construction and management strategies to prioritize safety, playability, and performance.