

EFFECTS OF ATHLETIC PAINTING ON TURFGRASS SOIL HEALTH AND
ATHLETE BIOMECHANICS

by

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(Under the Direction of Gerald M. Henry)

ABSTRACT

Athletic field painting is commonly conducted on natural turfgrass fields to create boundary lines and aesthetics for sporting events. Previous research has shown that paint pigments can suppress photosynthetic activity and cause declines in turfgrass quality. However, the focus of our research was to determine the potential effects of painting on soil characteristics, ryegrass germination, and athlete biomechanics. A comparison of two different soil moisture measurement sensors was first performed to establish a credible and rapid method to guide soil sample locations. Findings from laboratory and greenhouse studies suggest painting may cause an increase in bulk density, but no differences were observed with respect to perennial ryegrass germination. Athletes were recruited to perform maneuvers on painted and non-painted running lanes to determine peak accelerations and knee angles. However, biomechanics results varied among surfaces. Future research should consider further soil characteristics and athlete populations that may be affected by painting practices.

INDEX WORDS: Turfgrass, Painting, Soil health, Athlete biomechanics

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BS, University of Georgia, 2023

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial
Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2025

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August 2025

ACKNOWLEDGEMENTS

I'd like to thank my parents for their love and support throughout my life, and especially through my academic career. I feel so blessed to have a family that motivates me to do my best for the glory of God. The hard work they have displayed throughout their lives has been an inspiration to me, and I hope to make them proud with each passing day. I would not have been able to accomplish this without their encouragement.

I'd also like to thank Dr. Gerald Henry for taking a chance on me in my undergraduate years and allowing me the opportunity to further my education. The academic and life skills I have gained under his guidance are invaluable and will stay with me forever. Thank you also to my committee members, Dr. Nandita Gaur and Dr. Robert Lynall. Your time and dedication to advance my knowledge has meant so much to me.

Lastly, I'd like to thank Kevin Tucker, Dr. Erick Begitschke, Alberto Novello, and Dr. Julie Wang for showing me the ropes of research and being willing to help with anything. From the countless hours of driving to conferences to refining my mechanic skills to exploring new lunch spots in Athens, you all have been the best co-workers and friends. I also want to express my gratitude to Daniel Prince at Pace Academy, Jake Mays at The Westminster Schools, Nick Verrilli at Holy Innocents' Episcopal School, Adam Culpepper at Wesleyan School, and all the student athletes who participated in my research. Without you all, this would not be possible.

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CHAPTER 1

Literature Review

Sports Field Construction and Management

Natural turfgrass fields are commonly used as surfaces for recreational activities and athletic events that range from community level settings to collegiate and professional sports venues. Turfgrass species may be established via seed, sprigs, or sod, but specific methodology is often dictated by species, budget, and time (Christians et al., 2016). Bermudagrass (*Cynodon* spp.), seashore paspalum (*Paspalum vaginatum* Sw.), perennial ryegrass (*Lolium perenne* L.), Kentucky bluegrass (*Poa pratensis* L.), and tall fescue (*Festuca arundinacea* Schreb.) are routinely selected as sports field surfaces, but their use may depend on climate or sport (Puhalla et al., 2010). Climatic conditions play the biggest role in determining species utilization (Turgeon & Kaminski, 2019). In tropical and subtropical regions, warm-season turfgrasses like bermudagrass and seashore paspalum are planted, but turfgrass managers often overseed dormant turfgrass with perennial ryegrass or annual ryegrass (*Lolium multiflorum* Lam.) to maintain green color and an actively growing surface through winter months (Christians et al., 2016). Although turfgrass breeding efforts have expanded the environmental range of warm-season turfgrass species north of the transition zone, cool-season turfgrasses like perennial ryegrass, Kentucky bluegrass, and tall fescue are often preferred in cooler climates. Soil profiles are constructed with either native soil types or sand. Native soils can vary in texture with different combinations of sand (0.05 - 2.0 mm), silt (0.002 - 0.05 mm), and clay (< 0.002 mm) particles (James, 2015). Athletic fields constructed with

sand are either built with a native soil base that is capped with 15 cm of sand or composed according to United States Golf Association (USGA) specifications (Hummel, 1993). The USGA method consists of a compacted subgrade covered with 10 cm of pea gravel covered with 30 cm of a sand-based rootzone mix (9:1 sand to peat) (Puhalla et al., 2010). This construction allows for rapid, uniform water infiltration, adequate aeration and porosity, and the ability to withstand heavy traffic (Carrow & Petrovic, 1992; Puhalla et al., 2010; McCoy, 2015). Although mostly associated with sand-based systems, sports fields often employ drainage tile installed within the gravel layer for the removal of excess water.

Athletic fields require regular turfgrass inputs and maintenance practices to recover from wear/traffic stress and sustain uniform playing surfaces. Mowing is conducted to maintain field consistency and help reduce weed pressure, but height and frequency are dictated by turfgrass species and sport (Busey, 2003; Puhalla et al., 2010; McElroy & Bhowmik, 2013). Fertilizer is applied throughout the growing season to ensure aesthetic quality, canopy density, biotic and abiotic stress tolerance, and soil health (Lawson, 1989). Supplemental irrigation may be required in climates where natural rainfall events are not sufficient to maintain turfgrass health. Water applications can also reduce surface temperature and enhance ball movement (Wherley, 2011). Excessive wear and traffic from athletes can increase surface hardness and soil compaction, decrease water infiltration and gas exchange, and reduce root mass and depth (Carrow & Petrovic, 1992; Han et al., 2008). Cultivation practices like aerification and verticutting are performed during the playing season to rectify the aforementioned issues as well as reduce thatch layers and stimulate turfgrass vigor (Atkinson et al., 2012;

Turgeon & Kaminski, 2019). Applications of sand, soil, or other amendments are conducted to fill aerification holes, increase seed to soil contact during turfgrass establishment, and level uneven playing surfaces. (Spring et al., 2007; Kowalewski et al., 2010). Finally, turfgrass managers apply athletic field paint in the days just prior to game play.

Athletic Field Painting

Athletic field paints are most notably used to define areas of play on sports fields, but also add aesthetic value in the form of school logos or endzone patterns. Painting usually occurs weekly, but field use and level of traffic/wear may dictate more frequent applications to ensure design accuracy. Field paint is produced in aerosol cans or bulk containers, which often determines the technique and equipment used for their dispersal. Paint machines are most often utilized for large spaces whereas brushes and rollers are used in smaller areas or to clean up and define edges (Warnick, 2007; Wightman, 2007). Paints are manufactured to cause as little damage as possible to the turfgrass canopy by delivering complete leaf blade coverage while still allowing it to “breathe” (Puhalla et al., 2010). Many athletic field paints are water-based latex and have a common chemistry mixture of pigments, resins, solvents, and additives (Reynolds et al., 2012). While most of these components do not harm the plant, the pigments often inhibit photosynthetic activity. Specifically, titanium dioxide (TiO_2) and iron oxide (Fe_2O_3) pigments found in white and red paint, respectively, have been shown to reduce total carbohydrate production in perennial ryegrass (Reynolds et al., 2012).

Several studies have examined the effects of pigments and athletic field paint on the photosynthetic activity and physiological responses of different turfgrass systems.

McCarty et al. (2013) observed that paint reduced photosynthetically active radiation (PAR) of creeping bentgrass (*Agrostis stolonifera* L.) putting green plugs by 46%. Painting also hindered turfgrass health by decreasing the normalized difference vegetation index (NDVI), visual turfgrass quality, and percent cover of creeping bentgrass putting greens (McCarty et al., 2014). Not only do athletic field paints reduce photosynthetic activity, but their pigment color can also significantly influence the intensity of this phenomenon. Segars et al. (2024) reported that total canopy photosynthesis of 'Latitude 36' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] decreased 50.5% and 76.5% in response to white and black paint, respectively. The presence of paint also interferes with gas exchange associated with transpiration and subsequently increases turfgrass canopy temperature (Reynolds et al., 2016). Darker pigments such as black and blue were shown to exacerbate this trend on 'Tifway' hybrid bermudagrass (Reynolds et al., 2016). Canopy temperature was also reported to increase in overseeded perennial ryegrass systems in response to darker colored pigments such as black, green, and blue (Segars & Moss, 2014). Declines in turfgrass health and vigor over time due to sustained paint applications may increase the potential for athlete injury occurrence (Straw et al., 2019).

Soil Physical Properties

Soil disturbance as a result of physical and chemical inputs can alter the ability of plants to acquire nutrients and reduce water infiltration through the soil profile. Assessing the bulk density, field capacity, saturated hydraulic conductivity, and wilting point of a turfgrass system can aid in the detection of possible impacts from the presence of impeding layers within the soil profile such as paint. Furthermore, the accumulation of

athlete and vehicular traffic/wear on sports fields contributes to an increase in surface hardness and soil compaction over time. The effect of soil compaction can be assessed through bulk density measurements (Carrow, 1980). Bulk density is defined as the ratio of the mass of oven dry soil to the total volume of solids and pores (Hillel, 1982).

Contaminants that pollute the soil may also lead to greater bulk density values. Abosede (2013) reported that the presence of crude oil within the soil increased bulk density by 7.1%. Field capacity, defined as the amount of water retained within the soil following gravimetric water loss and downward movement, can be measured to assess plant available water. (Veihmeyer & Hendrickson, 1949). Reductions in field capacity could lead to acute drought stress, reduced nutrient uptake, and limited root proliferation (Mbagwu & Osuigwe, 1985; Fang et al., 2017). Changes to the soil profile structure, such as impervious layers, may increase field capacity and reduce water infiltration (Hillel, 1982).

Saturated hydraulic conductivity (K_{sat}) is a useful measurement for the examination of field drainage. It is a key soil property that describes how easily water can pass through a saturated soil profile (Usowicz & Liplec, 2021). If altered, turfgrass systems could experience oxygen deficiency, reduced nutrient availability, and root inhibition (Arvidsson, 1999; Dexter et al., 2004). Wilting point occurs when the osmotic potential is greater than the water potential and turgor pressure cannot be regained (Kopp & Jiang, 2013). Under significant drought stress, the addition of traffic to a turfgrass system would inevitably lead to a decrease in green canopy cover and turfgrass quality (Braun et al., 2020). Although these soil parameters have been studied in response to a variety of biotic and abiotic stresses, no previous research has examined their responses

to the prolonged presence of athletic field paint within the soil profile. Research may be warranted since a higher percentage of injuries often occur as athletes transition between variable field conditions (Straw et al., 2018).

Overseeding

As warm-season turfgrasses transition into dormancy during the fall, turfgrass managers often overseed sports fields in order to retain green cover and increase wear tolerance of the canopy. Perennial and annual ryegrass are frequently utilized for overseeding due to quick germination (Mazur & Rice, 1999). These species are also desirable due to their tolerance of biotic and abiotic stresses including insects, disease, wear, and temperature extremes (Puhalla et al., 2010). Aside from increasing canopy coverage and density, several other benefits to overseeding sports fields have been identified. Gannett et al. (2021) reported that in some cases, perennial ryegrass reduced broadleaf weed presence, thereby reducing the need for herbicide inputs. Ryegrass is also thought to provide a safer playing surface than other turfgrass species due to lower shoe-surface traction and better cushioning (Orchard, 2002). Overseeding has also been shown to lower bulk density values and increase total porosity presumably due to root growth and proliferation in the upper soil profile (Miller & Henderson, 2013).

Before overseeding, it is important to consider the environmental factors that may impact ryegrass germination and growth. Soil moisture and temperature are two of the most important elements that may affect the germination and establishment of turfgrass (Aronson et al., 1987; Shin et al., 2006). Light availability is also an imperative factor, since Gardner & Taylor (2002) reported that perennial ryegrass only resulted in 8.9% surface coverage when grown under moderate shade. Although shade is rarely a factor for

most sports field venues, the presence of field paint in the turfgrass canopy may produce similar shading effects. Impacts may be even more accentuated since overseeding typically occurs in the middle of a sporting season after several paint applications. Additionally, herbicidal removal of ryegrass the following spring has been more difficult in painted regions of the field (personal observation). This may be a result of reduced herbicide uptake due to lower field capacity in paint containing soils.

Performance Testing, Field Playability, and Athlete Safety

Turfgrass managers are tasked with assessing sports field conditions and performance before games in order to ensure consistency of play and safety. Several hand-held and mobile devices are available to accurately describe sports field plant and soil parameters. A common method for testing the robustness of a turfgrass stand is to determine the force that is required to tear the plant and associated roots (Straw et al., 2020). A shear vane comprised of a two-handled torque wrench attached to a shaft equipped with a studded disc or shear vane foot at the base is often used to measure this force, commonly referred to as shear strength, when inserted into the soil profile (Canaway & Bell, 1986; Straw et al., 2018). Soil moisture is often measured to help interpret field conditions. Time domain reflectometry (TDR) sensors equipped with two stainless steel probes are inserted into the soil to measure percent volumetric water content (%VWC) by relating it to the time it takes for an electromagnetic signal to travel from the datalogger and back (Jones et al., 2002; He et al., 2021). Soil compaction meters equipped with a 10 mm diameter shaft and 30° cone tip are slowly inserted into the soil profile at approximately 2.5 cm s⁻¹ to measure penetration resistance to a depth of 10 cm. A similar practice is conducted with a Clegg Impact Tester which measures soil

compaction in the upper 5 cm of the soil profile and is referred to as surface hardness. This device drops a 2.25 kg missile with an accelerometer through a guide tube from a height of 45 cm in order to measure the deceleration of the projectile on impact, which is reported in gravities (g) [American Society for Testing and Material (ASTM F1702), 2010]. Finally, field managers can assess green canopy cover using a normalized difference vegetation index (NDVI) meter held approximately 0.9 m above the turfgrass surface.

Recent studies have examined the correlation between field conditions and athlete injuries (Straw et al., 2018). Although the authors tangentially linked ground-derived injuries with specific soil/plant parameters, the exact field conditions at time of injury were not known. Therefore, further research is needed to evaluate the interaction of athletes with playing surfaces in “real time”. Force plates and wearable sensors are commonly used in biomechanics studies to measure kinetic and kinematic athlete responses as they interact with a variety of surfaces (Siegel et al., 2025). In the field, sensors such as wearable inertial measurement units (IMUs) collect athlete joint data in real time by using a gyroscope, accelerometer, and magnetic sensors to determine their location in space while simultaneously obtaining angular velocities or accelerations (Camomilla et al., 2018; Burbrink et al., 2023). The measurement of knee angles is of great importance since athletes are trained to land with increased knee flexion in order to decrease knee strain and prevent injuries. Furthermore, sports field surface characteristics may influence athlete knee flexion angles when landing or cutting. Smaller knee angles tend to suggest a higher risk of injury (Leppänen et al., 2017). Minimal to no research has examined the interaction between athletes and painted turfgrass surfaces. Since previous

research by Straw et al. (2018) reported higher injury incidence when athletes transitioned between variable field conditions, it is important to document the response of athletes to painted surfaces, especially since paint is variably applied to sports fields, further complicating the prediction of field performance.

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CHAPTER 2

SPATIAL COMPARISON OF ELECTROMAGNETIC INDUCTION WITH TRADITIONAL SOIL MOISTURE MEASUREMENTS ON ATHLETIC FIELDS

Abstract

The application of supplemental water through irrigation on natural turfgrass athletic fields is commonly conducted to ensure a uniform, healthy playing surface. As irrigation systems age, water may no longer be evenly applied to all areas of the field. Irrigation output distribution is commonly investigated through spatial maps of soil moisture. Time domain reflectometry sensors are widely used to collect volumetric water content (%VWC); however, their efficiency is limited. More recently, electromagnetic induction sensors that measure apparent electrical conductivity (ECa) have been utilized in agricultural systems to quickly gather information about soil physical and chemical properties. However, the direct correlation between these measurements is not widely known. The objective of this study was to compare a hand-held volumetric water content sensor to a mobile apparent electrical conductivity sensor. Georeferenced measurements of %VWC and ECa were recorded with a FieldScout TDR 300 sensor and an EM38-MK2 sensor, respectively, at four sand-based natural turfgrass fields. Soil samples were also obtained at each field in order to analyze soil conditions that may impact ECa measurements such as cation exchange capacity (CEC), organic matter (OM), and Na. Spatial maps were created in ArcGIS Pro through ordinary kriging and inverse distance weighting to visually compare the two sensors. While visual comparisons could be made at Holy Innocents' Episcopal School and Pace Academy, the comparisons were minimal at Wesleyan School and The Westminster Schools, which may be attributed to the variable range of ECa and %VWC values. This trend was also observed through the Pearson's product-moment correlation. Holy Innocents' Episcopal School and Pace Academy showed a moderate correlation at 0.57 and 0.53, respectively, while Wesleyan

School and The Westminster Schools showed a weak correlation at 0.03 and 0.23, respectively. Spatially constrained multivariate clustering was also conducted on ECa measurements in each field. %VWC points were spatially joined to these clusters for ANOVA analysis, which showed significance at Holy Innocent's Episcopal School and Pace Academy. Using the EM38-MK2 device in conjunction with baseline soil testing may be a faster method to measure soil moisture variability and create zones for site specific management.

Introduction

Sports fields are one of the most intensively managed turfgrass systems that require a multitude of inputs to maintain adequate playing surfaces. Excessive traffic and wear typically observed on community level sports complexes can cause reductions in the turfgrass canopy, while increases in surface hardness and soil compaction may reduce turfgrass rooting and shear strength (Carrow & Petrovic, 1992; Matthieu et al., 2011; Thoms et al., 2011). Therefore, irrigation systems are often required to supplement plant water needs in order to stimulate canopy recovery and maintain turfgrass growth. However, irrigation system accuracy may be reduced with age and without proper maintenance. Clogged nozzles, malfunctioning spray heads, and improper scheduling are just a few irrigation system deficiencies that can negatively impact accuracy (Carrow & Duncan, 2008; Carrow et al., 2010). Maintaining system performance is important since water deficient turfgrass may experience numerous physiological and metabolic disruptions including losses to both membrane and protein stability to reductions in photosynthetic capability (Hu et al., 2009; Jespersen et al., 2019; Lawlor & Cornic, 2002). Inadequate irrigation may also influence the effectiveness and safety of pesticides

and wetting agents that are required to be watered in following application (Kerr et al., 2019; Leinauer et al., 2007).

In turfgrass systems, the most common and widely used indicator of irrigation system performance is the lower quarter distribution uniformity (DUIq) (Burt et al., 1997). The calculation of DUIq is accomplished through the equidistant placement of catch can devices across the surface of an irrigated area, operation of the irrigation system for a predetermined time period, followed by the measurement of the amount of water within each can separately (Straw et al., 2018a). Although the DUIq method may provide insight into irrigation system distribution uniformity, it does not indicate the exact location of water infiltration nor redistribution (Baum et al., 2005; Straw et al., 2018a). Sensors that measure soil moisture in terms of volumetric water content (%VWC) are now more affordable and available to athletic field managers. Time domain reflectometry (TDR) sensors establish a direct relationship between %VWC and the time required for an electromagnetic signal to return to the datalogger (He et al., 2021; Jones et al., 2002; Topp & Davis, 1985). Georeferenced sensor data have been utilized to describe the spatial variability of soil moisture on athletic fields in an attempt to improve uniformity through precision turfgrass management (Straw et al., 2016; Straw et al., 2018a). However, the number of samples (approx. 115) and amount of labor required to accurately depict soil moisture variability of a sports field has limited the use of this technique (Straw et al., 2018b).

In recent years, apparent soil electrical conductivity (ECa) has become an invaluable tool in agriculture for the measurement of bulk electrical conductivity (Corwin & Lesch, 2005). Electromagnetic induction (EMI) sensors collect ECa data by using a

transmitter coil to generate a fluctuating magnetic field which penetrates into the soil, subsequently inducing secondary currents that are relayed back to a receiver coil (Doolittle & Brevik, 2014). However, these measurements may be influenced by soil physical and chemical properties including texture and salinity that can make interpretation of soil moisture more difficult. In fact, Martini et al. (2017) reported that soil moisture may have little influence on ECa measurements in soils with low clay content, but those EMI surveys were conducted on a hillslope terrain. Although crowned for improved drainage, athletic fields are predominantly level and often constructed on sand-based soil profiles (Puhalla et al., 2010). Most recently, Williams et al. (2024) reported that ECa data generated from an EMI traversing sand-capped golf course fairways was significantly correlated to measured soil water content. Given the variability in research findings, the small size of standard athletic fields, and the presence of manipulated soil profiles, EMI measurements may provide a quick and accurate tool for the interpretation of soil moisture. Therefore, the objective of our research was to compare apparent electrical conductivity data with volumetric soil water content measurements in order to determine the strength of potential correlations.

Materials and Methods

Field Descriptions

Research was conducted during May 2024 on four natural grass sports fields located throughout the Metro Atlanta area in GA. Locations included Pace Academy in Mableton, GA (33.8497° N, 84.4171° W), The Westminster Schools in Atlanta, GA (33.8419° N, 84.4341° W), Holy Innocents' Episcopal School in Atlanta, GA (33.9078° N, 84.4152° W), and Wesleyan School in Peachtree Corners, GA (33.9713° N, 84.2165°

W). Fields measured 48.8 m x 109.7 m and were primarily used for varsity sports including American football, soccer, and lacrosse. No renovation was conducted within the past five years and all fields were surfaced with hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy]. The hybrid bermudagrass cultivars at each location were as follows: ‘Tifway’ at Pace Academy, The Westminster Schools, and Holy Innocents’ Episcopal School; ‘TifTuf’ at Wesleyan School. Perennial ryegrass (*Lolium perenne* L.) was overseeded on each field yearly at a rate of 391 to 586 kg ha⁻¹ in the fall. Each field was constructed to United States Golf Association (USGA) specifications with a 31 to 41-cm depth sand rootzone (9:1 sand to peat mixture) placed above a 10-cm gravel layer with a drainage system installed below for the removal of excess water. Management practices for all locations included weekly irrigation at approximately 2.5 cm wk⁻¹ and regular painting of field boundary lines and school logos. A composite sample of 16 soil cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field, air-dried for 48 hours, sieved through a 2-mm mesh screen, and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA for analysis (**Table 2.1**). Sampling rings (6 cm height and 5.4 cm diameter) (SoilMoisture Equipment Corp., Goleta, CA) were driven into the soil profile until level with the surface. Samples were excavated intact, wrapped in plastic wrap to maintain integrity, and brought back to the lab in order to determine field capacity, wilting point, saturated hydraulic conductivity, and bulk density (**Table 2.2**). Field capacity was determined by setting up Tempe cell systems with ceramic plates (SoilMoisture Equipment Corp., Santa Barbara, CA) and applying pressure at -33 kPa for 48 hours. Wilting point and saturated hydraulic conductivity were examined with

automatic systems, such as the WP4C Dewpoint Potential Meter (METER Group, Inc., Pullman, WA) and the Chameleon single station system (SoilMoisture Equipment Corp., Santa Barbara, CA), respectively. Bulk density was determined by drying the samples in an oven at 105°C for at least 24 hours.

Data Collection

Fields were watered with an above-ground irrigation system with approximately 0.6 to 0.8 cm of water the afternoon before data collection occurred the following day if no rainfall event happened. Electromagnetic induction data points, EC_a, were collected by using the Geonics EM38-MK2 (Geonics Ltd., Mississauga, ON, Canada) and georeferenced with a Trimble GPS (Westminster, CO). The EM38-MK2 was calibrated according to the Geonics EM38-MK2 operating manual (Geonics, 2016). The sensor equipped with the GPS unit was towed behind a utility vehicle and traversed each field at a speed of 8 to 9.6 km h⁻¹ with downfield passes 9 m apart. A FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL) was utilized to record handheld %VWC data through time domain reflectometry (TDR). The TDR 300 has two stainless steel probes (5 mm diameter, 3.3 cm spacing, and 7.6 cm length) that were inserted into the soil in order to obtain measurements (an average of three readings) on a 9 x 9 m grid that were georeferenced with a Trimble GPS unit.

Data Analysis

Response variables of latitude, longitude, EC_a, and %VWC were downloaded and transferred to ArcGIS Pro version 3.2.0 (ESRI, Redlands, CA). *Geostatistical Analyst* was used to create spatial maps of EC_a through *ordinary kriging*. The conductivity of coil separation at 1.0 m in the horizontal mode (CH-1.0), or data from 0.75 m depth, was used

as the kriging variable. Empirical semi-variograms were fitted at the beginning to select the best model for kriging. Similarly to Straw et al. (2016), both spherical and exponential models were considered. There are many parameters that give information about semi-variogram performance and model selection; however, the model with a root mean square error (RSME) of ≤ 0.6 was selected. Semi-variogram parameters and their definitions are presented in **Table 2.3**. The spatial interpolation function *inverse distance weighting* (IDW) was utilized through *Geostatistical Analyst* to assign weights to known data points based on their distance in order to estimate values at unknown locations. Data points for %VWC were used as the input features and the power was optimized before finalizing the maps. The power controls the significance that the surrounding points have on the interpolated values which are determined by the inverse of the distance taken to the specified power. Soil moisture maps for handheld %VWC were created using IDW instead of kriging since there were less data points and the variability within some fields was relatively high. Both ECa and %VWC soil moisture maps were exported as raster maps and overlaid on a boundary for better visibility.

Although visual assessments were conducted to observe spatial trends between soil moisture maps, statistical measures were also used to determine correlations between the EM38-MK2 and TDR 300 sensors. Initially, raw ECa values at CH-1.0 m were extracted that spatially correlated with each %VWC data point. To determine the distance between the two values and the line of best fit, Pearson's product-moment correlation coefficient was obtained using the *cor.test* function in RStudio (Okoye and Hosseini, 2024). Scatterplots were also made with *ggplot2* to visualize the correlations. In ArcGIS, ECa kriged maps were subjected to *spatially constrained multivariate clustering* to group

E_{Ca} points using a pseudo-F statistic, which calculates the optimal number of clusters. The number of clusters between 2 and 30 that are associated with the largest pseudo-F statistic are utilized. The largest pseudo-F statistic value indicates clustering solutions that most effectively increases similarity within clusters while enhancing differences between them. The “Trimmed Delauney Triangulation” option was also used to ensure feature neighbors are close in proximity. This function takes space coordinates and E_{Ca} points to create clusters that are as similar as possible. Each cluster contains data points that are most like one another, while being distinctly different from those in other clusters. Clusters were then spatially joined to %VWC points through the matching option “closest.” To determine the significance of cluster ID and their related soil moisture, the spatially joined tables were transferred to RStudio where analysis of variance tests were performed using the *aov* function.

Results and Discussion

Both the median and spatial distribution of soil moisture varied between each school when comparing E_{Ca} data generated by the mobile EM38-MK2 and %VWC data from the handheld TDR 300 (**Fig. 2.1**). At Pace Academy, The Westminster Schools, and Wesleyan School, the median soil moisture was higher with the handheld TDR 300 device. However, at Holy Innocents’ Episcopal School, the median soil moisture for the handheld device was slightly lower than the mobile EM38-MK2 unit ($\approx 12.6\%$ and 18.7 mS m^{-1} , respectively).

Pearson’s correlation coefficients between the mobile E_{Ca} and the handheld %VWC data ranged from 0.53 to 0.57 for Pace Academy and Holy Innocents’ Episcopal School (**Table 2.4**), indicating a moderate relationship between the two sampling

methods. Contrarily, Wesleyan School and The Westminster Schools had low correlation coefficients (0.03 and 0.23, respectively) and correlations at each field were non-significant. Examination of generated scatterplots revealed similar trends as the Pearson's correlation coefficients between sampling methods for each of the four fields (**Fig. 2.1**). The semi-variogram parameters used to generate spatial maps of ECa and the root mean square error (RMSE) outputs are presented in **Table 2.5** while the IDW summary statistics for %VWC are presented in **Table 2.6**. Exponential or spherical models were used to fit semi-variograms. The IDW and kriged maps of soil moisture are presented in **Fig. 2.2**.

Patterns of soil moisture variability between sampling devices were only comparable for Pace Academy and Holy Innocents' Episcopal School. Contrasts in moisture patterns down the right side of The Westminster Schools maps highlighted a minor difference in variability which was further confirmed by the soil moisture scale generated for each map (6.0% to 57.6% for IDW and 5.4 mS m⁻¹ to 34.3 mS m⁻¹ for kriged) (**Fig. 2.2**). Furthermore, a major difference in variability was detected at Wesleyan School which is apparent by the dissimilar patterns between the two sampling devices and the substantial differences in the magnitude of soil moisture for IDW and kriged maps (18.5% to 41.5% and 8.1 mS m⁻¹ to 17.4 mS m⁻¹, respectively).

Spatially constrained multivariate clustering analysis revealed significant variance between moisture values for Pace Academy and Holy Innocents' Episcopal School, further confirming visual map interpretations and Pearson's correlation coefficients (**Table 2.7**). Although significant, the number of clusters for Pace Academy is relatively high (8), which may complicate attempts to site specifically manage soil moisture within

that specific field. Contrarily, Holy Innocents' Episcopal School was not only significant but had a low number of identified clusters (4). Differences in cluster number between fields could be rectified by configuring the desired number of clusters in ArcGIS prior to analysis instead of reliance on the pseudo-F statistic.

The differences in soil moisture measurements obtained from the mobile EM38-MK2 and the TDR 300 may explain the observance of moderate correlations on only two of the four sports fields. Although both sensors use electromagnetic waves to measure soil moisture, they differ in frequency and the analysis of those generated signals. EMI sensors generate a magnetic field in the soil to measure the apparent electrical conductivity, or the ability of the soil to conduct electricity (Corwin & Lesch, 2003; Doolittle & Brevik, 2014). Contrarily, a TDR sensor measures the amount of time that a high-frequency pulse travels through the soil in order to determine the dielectric constant, or the ability of the soil to store electrical energy (Topp et al., 1980; Roth et al., 1992). This difference in measurement may lead to variations in accuracy and application suitability. Additionally, the mobile EM38-MK2 and the TDR 300 measure soil moisture to different depths. The TDR 300 typically measures soil moisture to a maximum depth of 20 cm, dependent on the attached probe length, while the EM38-MK2 measures soil moisture to a depth between 0.38 and 0.75 m in the horizontal dipole mode (Geonics, 2016). The ability of the TDR 300 to detect soil moisture at shallower depths may explain why the median soil moisture was higher at three of the four sports fields. Moreover, the median values detected at the Holy Innocents' Episcopal School field was relatively low, 12.6% for the TDR 300 and 18.7 mS m⁻¹ for the EM38-MK2, making differences between the two sensors more negligible.

Similarly, Williams et al. (2024) also observed moderate correlation coefficients (0.40 to 0.62) for ECa data generated with a DUALEM-1S electromagnetic induction (EMI) sensor and %VWC data generated with the Toro Precision Sense 6000 (PS6000) on sand-capped (20.3 cm depth) hybrid bermudagrass and zoysiagrass [*Zoysia matrella* (L.) Merr.] golf course fairways. However, the PS6000 is a mobile device that utilizes probes that are 2.5 cm longer than the TDR 300 probes. A temporary perched water table may be created above the smaller pores of the clay layer as water moves through the above sand-based profile (Turgeon & Kaminski, 2019). Therefore, positive correlations between the DUALEM-1S and the PS6000 may be related to the greater soil profile accessibility of the PS6000 compared to the TDR 300. Contrarily, Straw et al. (2016) observed high correlation coefficients (0.68 to 0.85) on three of four hybrid bermudagrass athletic fields when comparing %VWC obtained with a handheld TDR 300 and the PS6000. Although Straw et al. (2016) compared a handheld with a mobile device, the two sampling methods employed were very similar; therefore, measurements were expected to be similar between the two devices (Gardner et al., 1998).

Many soil parameters can influence ECa data acquisition and reliability including soil salinity, organic matter (OM) and clay content, and cation exchange capacity (CEC) (Corwin & Scudiero, 2016; Sudduth et al., 2001). Williams & Baker (1982) was able to explain 65 to 70% of the soil moisture variability in salt-affected soils by examining the concentration and presence of soluble salts. Wesleyan School, the field with the lowest correlation coefficient (0.03), also had the least amount of Na (9.6 kg ha^{-1}) compared to the other three schools (21.2 to 29.7 kg ha^{-1}), which could explain the weak correlation between ECa and %VWC (**Table 2.1, 2.4, and 2.7**). However, OM content, soil texture,

and CEC tend to dictate variations in conductivity within non-saline soils (Corwin and Lesch, 2005). Kelley et al. (2017) reported that soil texture impacted the accuracy of electromagnetic induction. Again, the field at Wesleyan School had the lowest OM content (0.56%), clay content (1.08%), and CEC (0.46) compared to the other three schools (**Table 2.1**).

Sampling for soil moisture can be useful for the delineation of site-specific management units in order to implement precision turfgrass management or the assessment of irrigation system application efficiency (Krum et al., 2010; Straw et al., 2018a; Straw & Henry, 2018). The introduction of mobile sampling devices such as the EM38-MK2 was intended to expedite site analysis and increase data collection leading to enhanced assessment accuracy. A minimum of 100 samples are necessary for the creation of a dependable semi-variogram for kriging while sampling on a 4.8 m x 9.6 m grid (115 samples) is required to accurately describe the spatial variability of soil moisture on a typical American football field (Oliver & Webster, 2014; Straw et al., 2018b). Recording samples with a handheld device on the grid spacing previously described would be impractical due to the required time investment. It took approximately 1 hr to record %VWC across each field in our research. Furthermore, the addition of a GPS unit to georeference handheld soil moisture readings required a second person to participate in the data acquisition. The mobile EM38-MK2 was able to traverse each field in approximately 15 minutes; however, these devices are very expensive and can be difficult for field managers to obtain. Therefore, the handheld TDR 300 sensor is a more cost effective, easily purchased option, but requires more time and labor.

Conclusions

The strength of relationships between mobile ECa and handheld %VWC data on sand-based soil profiles varied from one field to the next. Moderate spatial relationships were only observed on two of the four athletic fields. Soil parameters including Na, OM content, clay content, and CEC may have influenced the strength of the relationships between ECa and %VWC; therefore, it is important to conduct soil tests prior to sampling in order to provide baseline information for each site. Sampling athletic fields for soil moisture with the handheld TDR 300 may be limited due to the amount of time and labor required, while sampling with the mobile EM38-MK2 device is relatively quick and allows for intensive spatial assessment. Both soil moisture medians and data distributions varied within handheld and mobile acquisitions; therefore, in order to reduce fluctuations in test results, it is important to maintain device consistency and performance over time. Maps of ECa and %VWC displayed similar patterns of variability, but at different magnitudes. This may be related to the differences in soil depth that each moisture sensor is capable of assessing. Therefore, handheld and mobile devices can produce similar results when detecting variability of soil moisture within a field if certain cautions are taken prior to sampling. The positive relationship observed between ECa and %VWC can be used to site specifically apply irrigation. For instance, areas with low ECa may need more frequent irrigation compared to areas with high ECa. Therefore, the use of the mobile EM38-MK2 device could provide turfgrass managers with a rapid, reliable method of assessing soil moisture variability on athletic fields that improves irrigation efficiency and subsequent plant health and field performance.

Acknowledgements

Thank you to Daniel Prince at Pace Academy, Jake Mays at The Westminster Schools, Nick Verrilli at Holy Innocents' Episcopal School, and Adam Culpepper at Wesleyan School for allowing us to use their fields for testing.

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Table 2.1. Laboratory soil analysis^a for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	pH	CEC	OM	Sand	Silt	Clay	P	K	Ca	Na	Mg	Fe
	%						kg ha ⁻¹					
Pace Academy	4.96	1.78	2.26	95.9	2.06	2.08	5.6	49.2	95.6	29.1	28.9	111.1
The Westminster Schools	6.27	6.58	2.58	94.8	3.10	2.08	79.4	75.5	1179.8	29.7	64.8	126.2
Holy Innocents' Episcopal	4.89	4.16	3.62	93.8	4.14	2.08	47.3	86.2	341.3	21.2	29.8	186.2
Wesleyan School	5.47	0.46	0.56	98.8	0.14	1.08	7.9	23.6	42.8	9.6	16.1	31.3

^aA composite sample of 16 cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA

Table 2.2. Soil parameters^a measured for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	Field Capacity($\text{cm}^3 \text{cm}^{-3}$) ^b	Wilting Point(%)	Ksat ^c (cm min^{-1})	Bulk Density (g cm^{-3})
Pace Academy	0.25	2.0	0.41	1.0
The Westminster Schools	0.30	3.4	0.20	1.0
Holy Innocents' Episcopal	0.14	3.1	0.20	0.96
Wesleyan School	0.21	1.5	0.78	0.95

^aMeans for all parameters are based off of 16 samples obtained throughout each field.

^bField capacity and saturated hydraulic conductivity were directly measured by fitting sampling rings into a Tempe cell system while wilting point and bulk density were determined from a soil sample removed from the larger sampling ring source.

^cAbbreviations: Ksat, saturated hydraulic conductivity.

Table 2.3. Semi-variogram parameters and their respective definitions.

Semi-variogram Parameter	Definition
Lag Size	The space or gap measured between the central points of adjacent bins.
Nugget	Measurement error or fluctuation that falls below the data's resolution threshold.
Major Range	The point at which the semi-variance reaches a stable value.
Partial Sill	The variation in a spatially autocorrelated process, excluding the influence of the nugget effect.

Table 2.4. Correlation coefficients^a between ECa and handheld %VWC data acquisition at Pace Academy, The Westminster Schools, Holy Innocents' Episcopal, and Wesleyan School.

School Name	Pearson's Correlation Coefficient
Pace Academy	0.53 ***
The Westminster Schools	0.23 NS
Holy Innocents' Episcopal	0.57 ***
Wesleyan School	0.03 NS

^{NS}, ***Nonsignificant or significant at $P < 0.001$, respectively.

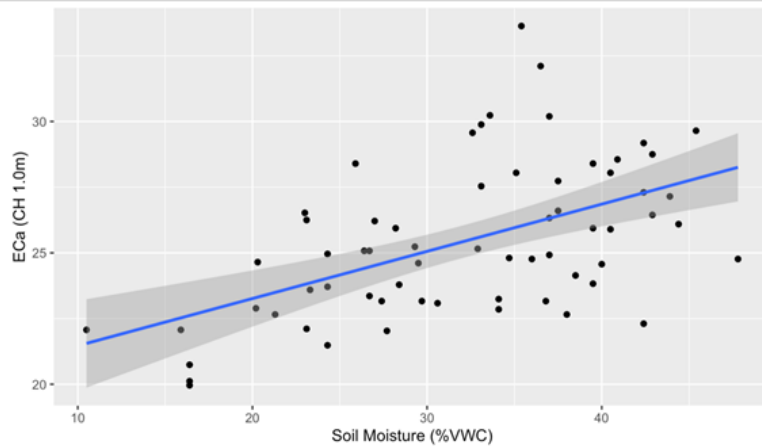
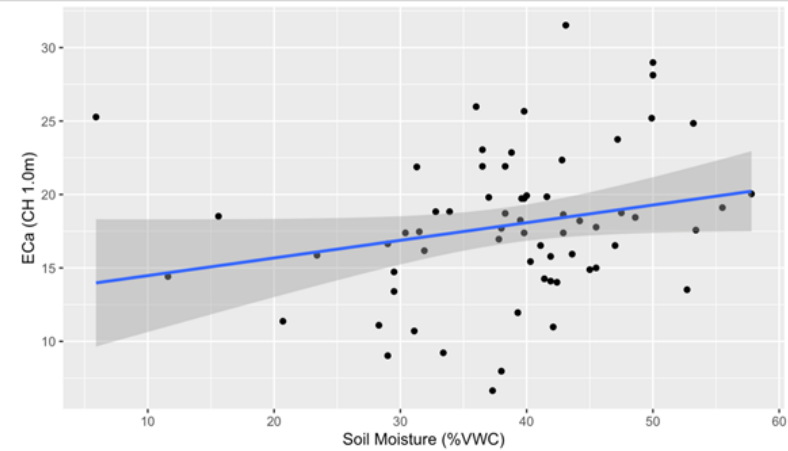
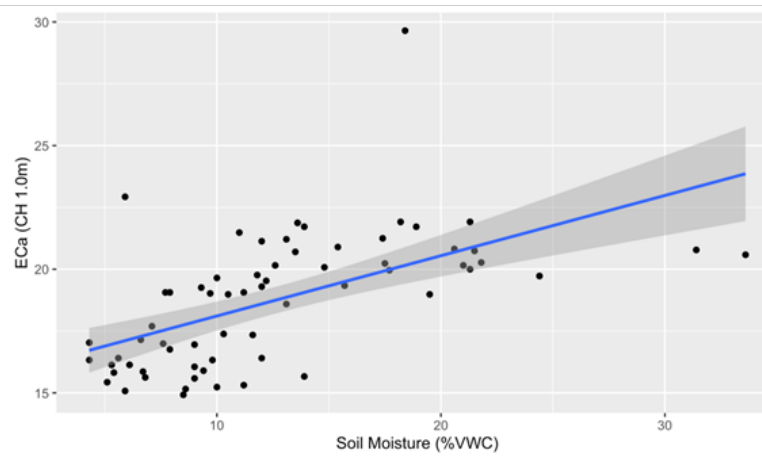
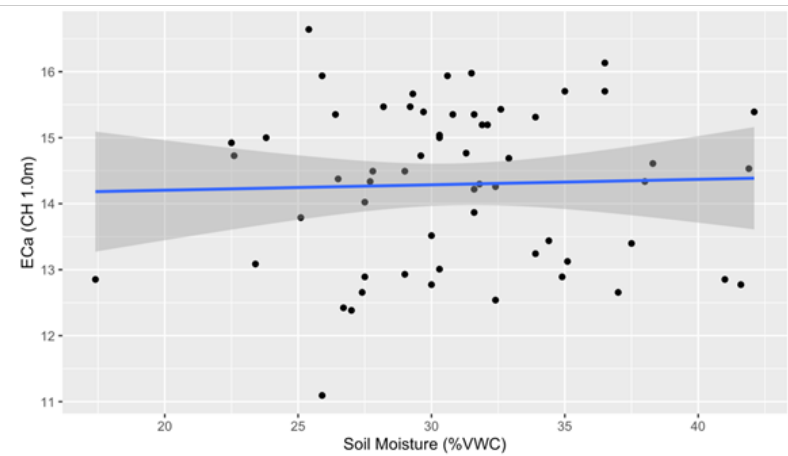
Pace Academy**The Westminster Schools****Holy Innocents' Episcopal****Wesleyan School**

Figure 2.1. Scatterplots made with ggplot2 for Pace Academy, The Westminster Schools, Holy Innocents' Episcopal School, and Wesleyan School.

Table 2.5. Semivariogram parameters of ECa for each school.

School Name	Count	Nugget	Partial Sill	Range	Lag Size	Model ^a	RMSE ^b	RMSE Standardized	Average SE
Pace Academy	3139	0.02	3.5	6.6	8.2	Spherical	0.40	0.78	0.55
The Westminster School	2780	0	15.6	0.0002	3.1	Exponential	0.61	1.03	0.76
Holy Innocents' Episcopal	3644	0	3.3	3.0	3.7	Spherical	0.41	0.63	0.72
Wesleyan School	3386	0.05	0.5	3.8	4.7	Spherical	0.35	0.98	0.37

^aThe model was selected based on best visual fit from exponential or spherical.

^bAbbreviations: root mean squared error, RMSE; standard error, SE.

Table 2.6. Inverse distance weighting (IDW) summary statistics for %VWC for each school.

School Name	Power	Count	RMSE (%VCW) ^a
Pace Academy	5.4	64	5.2
The Westminster Schools	1.7	65	9.1
Holy Innocents' Episcopal	4.6	65	4.2
Wesleyan School	1.0	60	5.2

^aAbbreviations: root mean squared error, RMSE.

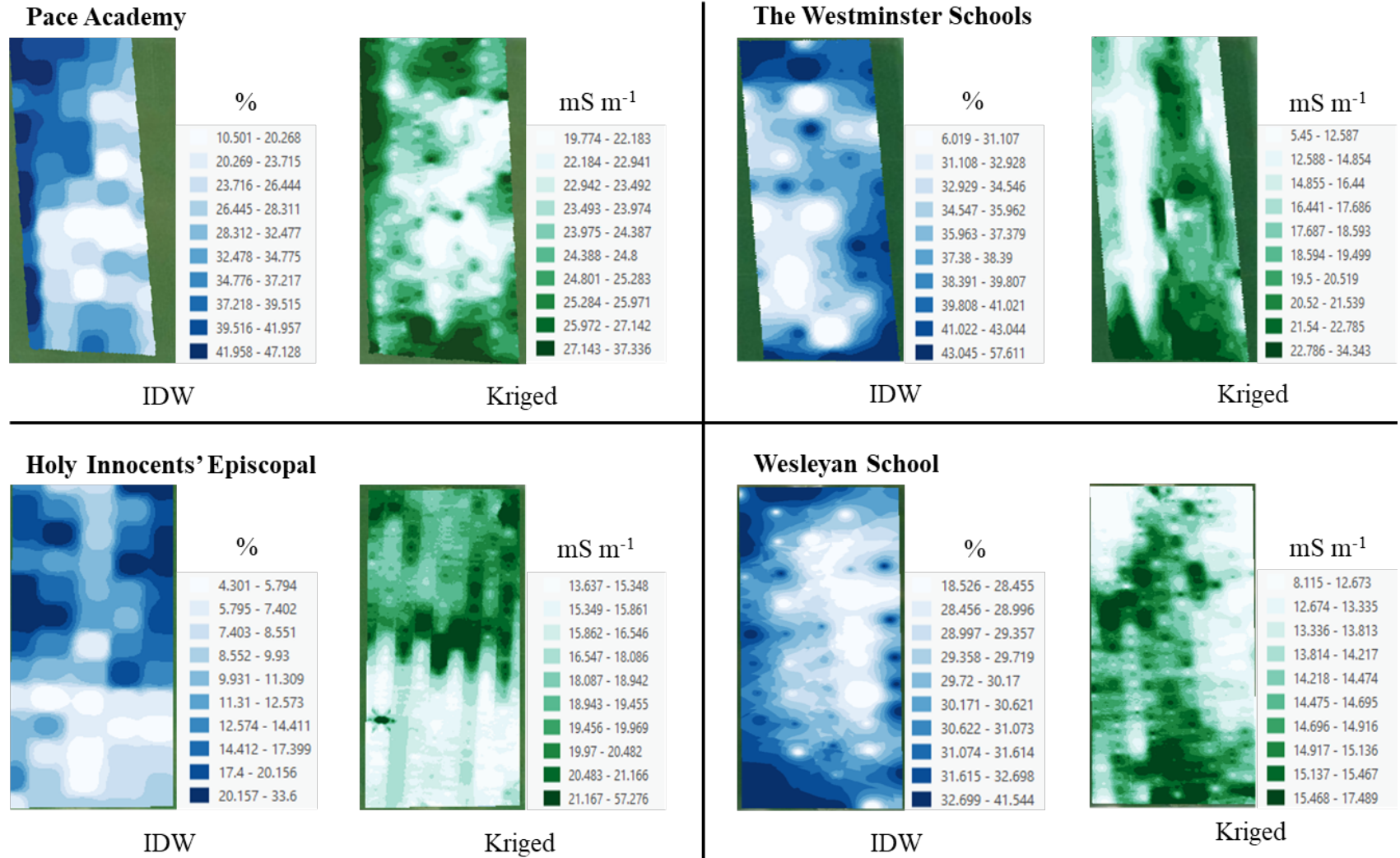


Figure 2.2. IDW and kriged maps of soil moisture on sand-based sports fields at Pace Academy, The Westminster Schools, Holy Innocents' Episcopal School, and Wesleyan School. Abbreviation: IDW, inverse distance weighting.

Table 2.7. Spatially constrained multivariate clustering ANOVAs.

School	Number of clusters	p-value
Pace Academy	8	0.00666 **
The Westminster Schools	9	0.553 NS
Holy Innocents' Episcopal	4	2.78e-07 ***
Wesleyan School	2	0.293 NS

NS, *, **Nonsignificant, significant at $P < 0.01$, and significant at $P < 0.001$, respectively.

CHAPTER 3
LONG-TERM USE OF ATHLETIC FIELD PAINT AFFECTS SOIL PHYSICAL
PROPERTIES

Abstract

Applying athletic field paint is a routine practice that many turfgrass managers perform in order to provide boundary lines and aesthetics for various sporting events. However, paint components, such as pigments, resins, solvents, and additives, may have the potential to disrupt turfgrass and soil health. Therefore, the objective of our research was to determine the potential effects of painting on soil characteristics including bulk density, field capacity, saturated hydraulic conductivity, and wilting point. Laboratory testing was conducted with soil samples obtained from painted and non-painted areas of four high school football fields built with USGA specifications in the Metro Atlanta area in GA. While significant differences varied, trends of certain parameter means were observed between schools. Bulk density was observed to be higher in painted samples compared to non-painted samples in three of the four fields. This was the only parameter that favored treatment as a fixed effect when linear mixed effect models were performed to determine if the age of the field or the number of painting applications had an impact on soil characteristics. Field capacity was higher while saturated hydraulic conductivity was lower for non-painted areas in three of the four schools. However, for wilting point, two of the schools had higher values for painted areas while the other two schools had higher values for non-painted areas. Increases in bulk density may occur in response to painting applications, further contributing to the variability of field soil parameters and potentially heightening athlete injuries and reducing playability. Therefore, changes in cultural practices that aim to alleviate soil compaction such as aeration may be necessary in painted areas of the field.

Introduction

Turfgrass managers apply athletic paints to field surfaces in order to create boundary lines and logos that provide direction and aesthetics for a range of sporting events (Puhalla et al., 2010). Most of these paints are water-based latex containing a variety of pigments, resins, solvents, and additives, so application is required weekly during field play (Reynolds, 2012). Although responsible for different chemical functions, each of these paint constituents has the potential to disrupt turfgrass and soil health. The accumulation of paint over time has been associated with disruption of light in the visible spectrum reaching the leaf surface and therefore, a decrease in the photosynthetic activity of the turfgrass canopy (Reynolds, 2012). In fact, Segars and Moss (2014) observed a reduction in photosynthesis when turfgrass foliage was covered in darker paint colors while canopy temperatures increased in response to the colors black and green. Decreases in photosynthetic activity often translate to reductions in turfgrass quality through canopy thinning (McBee, 1969). Reductions in leaf water-soluble carbohydrate content of > 40% in response to paint presence further demonstrates potential long-term impacts on turfgrass health (Segars et al., 2024).

Hollow-core aerification practices conducted on sand-based soil profiles often reveal paint migration from surface applications to depths approaching 15 cm. This has been confirmed through several soil media posts depicting field pictures following aerification or soil samples obtained by turfgrass managers (personal observation). Monetary costs, labor, and disruption in play often limit the frequency of athletic field renovation; therefore, paint penetration can be exacerbated over time. It is unknown whether athletic field paint adsorbs to soil particles impacting pore size or solubilizes in the soil solution, but many soil physical properties may be influenced or altered by its'

presence. Soil characteristics such as field capacity, saturated hydraulic conductivity, wilting point, and bulk density may be examined to determine soil functionality within a turfgrass system. Field capacity, defined as the amount of water held by soil following the removal of gravimetric water and cessation of downward movement, can be measured to help determine effective plant available water (Veihmeyer and Hendrickson, 1949). Alterations to field capacity could initiate acute drought stress, reduce nutrient uptake, and limit root proliferation (Mbagwu and Osuigwe, 1985; Fang et al. 2017). Saturated hydraulic conductivity (K_{sat}) is the measure of how readily water can pass through saturated soil and can be used to determine athletic field drainage (Usovicz and Lipiec, 2021). Changes to saturated hydraulic conductivity might result in oxygen deficiency, reduced nutrient availability, and root inhibition (Dexter et al., 2004; Arvidsson, 1999).

Application variability of painting practices in combination with potential changes to soil physical properties and function may further complicate turfgrass management and athletic field performance. Irrigation inputs may result in uneven field saturation while compromised root growth can decrease playability and subsequently increase the probability of athlete injuries. The identification of specific soil characteristics affected by the presence of athletic field paint could modify current management practices to account for within-field variability. Therefore, the objective of our research was to determine whether the presence of athletic field paint within the soil profile impacts soil physical properties and functionality.

Materials and Methods

Field Descriptions

Research was conducted in the summer of 2024 at four natural grass sports fields located throughout the Metro Atlanta area in GA. Locations included Pace Academy in Mableton, GA (33.8497° N, 84.4171° W), The Westminster Schools in Atlanta, GA (33.8419° N, 84.4341° W), Holy Innocents' Episcopal School in Atlanta, GA (33.9078° N, 84.4152° W), and Wesleyan School in Peachtree Corners, GA (33.9713° N, 84.2165° W). Fields measured 48.8 m x 109.7 m and were primarily used for varsity level sports including American football, soccer, and lacrosse. No renovation was conducted within the past five years and all fields were surfaced with hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy]. The hybrid bermudagrass cultivars at each location were as follows: 'Tifway' at Pace Academy, The Westminster Schools, and Holy Innocents' Episcopal School; 'TifTuf' at Wesleyan School. Perennial ryegrass (*Lolium perenne* L.) was overseeded on each field yearly at a rate of 391 to 586 kg ha⁻¹ in the fall. Each field was constructed to United States Golf Association (USGA) specifications with a 31 to 41-cm depth sand rootzone (9:1 sand to peat mixture) placed above a 10-cm gravel layer with a drainage system installed below for the removal of excess water. Management practices for all locations included weekly irrigation at approximately 2.5 cm wk⁻¹ and regular painting of field boundary lines and school logos. A composite sample of 16 soil cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field, air-dried for 48 hours, sieved through a 2-mm mesh screen, and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA for analysis (**Table 3.1**). Field ages (since last renovation) and number of painting applications per year are presented in **Table 3.2**.

Sample Collection

Volumetric water content (%VWC) maps were created to guide sampling areas within each field in order to account for any underlying conditions related to soil moisture. A FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL) was utilized to record %VWC measurements (an average of three readings) on a 9 x 9 m grid. Readings were georeferenced with a Trimble GPS unit. Soil moisture (%VWC) data was analyzed with ArcGIS Pro version 3.2.0 (ESRI, Redlands, CA). Soil moisture data based on the observed range of values in our four fields were interpolated using the inverse distance weighting (IDW) method to create continuous raster maps.

The soil moisture range in which samples were collected at each location were as follows: 20-30 %VWC at Pace Academy and Wesleyan School, 40-45 %VWC at The Westminster Schools, and 12-25 %VWC at Holy Innocents' Episcopal School. Soil sample locations were based on %VWC in order to help reduce sample variability. Eight non-painted and eight painted samples were collected with sampling rings (6 cm height and 5.4 cm diameter, SoilMoisture Equipment Corp., Santa Barbara, CA). The rings were hammered into the ground using a rubber mallet and a wooden block for stability until the top of the ring was flush with the soil surface. Rings were dug out of the ground and any remaining soil on the bottom of the ring was leveled with a soil knife before being sealed with plastic wrap to maintain the integrity of the field weight before and during transport. Samples were refrigerated at 4°C until laboratory experiments were initiated.

Laboratory Testing

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) was calculated using the automated, Chameleon single-station system and the associated Monitor Transducer software

(SoilMoisture Equipment Corp., Santa Barbara, CA) using the constant head method. To calibrate the system, an empty sample ring (5.9 cm height, 5.4 cm diameter) was set up in a Tempe cell system that was attached to a water reservoir. A zero head height is established by lowering the air tube into the water reservoir until the Tempe cell stopped dripping and the air tube stopped bubbling. The zero head height was used as a reference when setting the desired constant head height of 8.5 cm.

Samples were allowed to fully saturate and stabilize by turning on the water reservoir valve until the system started dripping at a constant rate and the air tube was bubbling. After saturation, the Monitor Transducer was connected to the Chameleon software and data points were collected in 10 equal increments and allowed to run for 10 minutes according to the operating instructions (SoilMoisture Equipment Corp., 2016). After the reading period was complete, the first and last collected data point was used to calculate an average K_{sat} value in cm min⁻¹.

Field Capacity

Following sample saturation during the K_{sat} process, each sample ring was set up in another Tempe cell system with a ceramic plate (SoilMoisture Equipment Corp., Santa Barbara, CA). These systems were attached to air tubes that supplied pressure at a constant rate of -33 kPa. Any detectable pressure leaks in the system were sealed with Parafilm (American Can Co., Greenwich, CT). Samples were removed from the system after 48 hours of pressure or until water was no longer continuously pushed out of the system. Weights of the Tempe cell system, sampling ring, soil at field capacity, air-dried soil, and bulk density were recorded in order to calculate field capacity:

$$\theta g = (g \text{ water lost}) / (g \text{ oven dry soil})$$

$$\text{Field Capacity} = (\theta_g * \rho_b) / 1$$

Bulk Density

Between 18-20 g of air-dried soil was removed from each sample ring and placed in aluminum tins. These tins were placed in an oven at 105°C for at least 24 hours or until a constant weight was reached. Bulk density (g cm^{-3}) was calculated with the following equation:

$$\text{OD weight ratio} = (\text{Oven dry soil in tin} * \text{Total air dry weight of soil}) / (\text{Air dry soil in tin})$$

$$\text{Bulk density } (\rho_b) = \frac{\text{OD weight ratio}}{\text{volume of soil ring}}$$

Wilting Point

The WP4C Dewpoint PotentiaMeter (METER Group, Inc., Pullman, WA) was used to gather wilting point values. Air dried soil was placed into a stainless-steel sample cup until it covered the bottom and was half full. Any soil particles on the rim of the cup were cleaned off with a Kimwipe (Kimberly-Clark Professionals, Irving, TX). The sample cup was placed in the machine and allowed to warm until the difference between the temperature of the sample and the temperature of the chamber block ($T_s - T_b$) was between 0.50-0. Once at a desirable temperature, the sample reading was initiated and run on precise mode. After the first run, 1-2.5 mL of deionized water was added to the sample and the process was repeated. Megapascal (mPa) values from dry and wet readings were recorded. The difference in gravimetric water content between the dry and wet runs were multiplied by bulk density in order to configure the wilting point for each sample.

Data Analysis

All data analyses were conducted in R version 4.3.1. The Kruskal-Wallis Test was utilized using the *kruskal.test* function. If laboratory errors occurred resulting in any field capacity values of zero, these points were deleted from the dataset. Field capacity data was not normally distributed; therefore, the Kruskal-Wallis test was used to perform a non-parametric, one-way analysis of variance to determine whether there are significant differences between the medians of three or more independent groups (Kruskal & Wallis, 1952). An H-statistic, given to determine variance in ranks, closely follows the chi-squared distribution (McKight and Najab, 2010). Although no values were removed from the other soil physical properties tested, this analysis was used across all parameters to ensure that comparisons were uniform.

Linear mixed effects models were conducted using the function *lmer* to test variability across schools for each soil parameter. Several models were created to determine if other variables, such as field age, the amount of paint applications, or possible interactions influenced each soil parameter. A list of these models can be found in **Table 3.3**. Corrected Akaike information criterion (AICc) values were used to determine the best model.

Results and Discussion

Bulk Density

Bulk density of painted samples was significantly different than non-painted samples at Pace Academy and The Westminster Schools (**Table 3.4**). However, the mean bulk density in painted samples was higher than non-painted samples across all schools except Holy Innocents' Episcopal School. Similarly, increases in bulk density have been observed with the added presence of soil pollutants. Abosede (2013) reported a 7.1%

increase in bulk density of a loamy sand soil when contaminated with crude oil compared to non-polluted soil. The addition of microplastics may also alter soil pore space, subsequently affecting bulk density (de Souza Machado et al., 2018). Han et al. (2024) observed an increase of microaggregates from 17% to 32% and a reduction in macroaggregates from 84% to 68% in microplastic polluted soils due to a decline in particle binding agents as a result of less microbial activity and subsequent byproduct production. Therefore, the addition of athletic field paint to the soil profile, like pollutants, may modify soil structure and thereby lead to an increase in bulk density. However, an increase in bulk density was not observed at Holy Innocents' Episcopal School, which may be related to the amount of time between field renovations (18 years). The high accumulation of organic matter detected in the initial soil analysis in conjunction with traffic stress may have contributed to an increase in soil compaction over time, reducing the impact of athletic field paint on bulk density (Carrow, 1980); however, soil compaction was not measured in our research.

After running linear mixed effect models to determine other variables and interactions that may affect the tested soil parameters, bulk density was the only parameter that favored the model with treatment as a fixed effect. All other parameters preferred the null model which only contained school as a random effect. The average effect of the independent variable of treatment further shows the effect of paint on bulk density. Discrepancies observed in field capacity, wilting point, and saturated hydraulic conductivity may be due to the sampling technique. Samples were obtained from areas of similar soil moisture content; however, these parameters are often used to explain

differences in water holding capacity. This may explain the lack of impact reported for other factors.

Field Capacity

Field capacity was only significantly different between painted and non-painted samples at The Westminster Schools and Wesleyan School; however, the results were opposite, with non-painted samples exhibiting greater field capacity at Wesleyan School (**Table 3.4**). Although not significant, field capacity was also greater for non-painted samples at Pace Academy and Holy Innocents' Episcopal School. Dissimilarly, Liu et al. (2017) reported that the addition of biochar to sand increased water retention due to disruptions in soil compaction and increases in interpores created by the elongated shape of biochar particles present within the sand mixture. Paint in our research was observed evenly distributed throughout excavated soil samples to depths approaching 15 cm, which may have reduced the impervious surface response (altered field capacity and water infiltration) typically observed in some native soils containing a more concentrated layer of paint near the soil surface (Hillel, 1982).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was only significantly different at The Westminster Schools with non-painted samples resulting in higher K_{sat} values than painted samples (**Table 3.4**). Although not significant, mean K_{sat} was greater for painted samples at each of the other three schools compared to non-painted samples. This observation was opposite of what we expected, since we theorized that paint present within the soil profile would clog pores, leading to a reduction in water infiltration. Wei et al. (2020) reported a reduction in K_{sat} between 39.6% and 81.7% of three different soil

textures in response to 4% w/w crude oil pollution, while Cook et al. (1994) observed a 50% reduction in ponded infiltration rates of a sandy loam soil after 32 months of wastewater irrigation treatments. Similarly, both of these studies theorized that reductions in K_{sat} were caused by the clogging of soil pores. Therefore, soil type and paint distribution within the soil profile may have played a role in the observed differences in water infiltration between our research and those reported from other contaminated soil experiments. United States Golf Association spec sand mixtures are engineered for rapid infiltration, so the presence of large pore spaces encourage gravimetric water flow, while the large distribution of paint throughout the soil profile may lessen the overall impact of paint presence on pore size. Furthermore, Wei et al. (2020) observed the lowest reduction in K_{sat} of a sandy loam (39.6%) compared to a light loam (81.7%) and a heavy loam (52.8%) polluted with oil when contrasted with non-polluted soils of the same texture. This may further emphasize a reduction in paint influence on sand-based versus native athletic field profiles.

Wilting Point

The only significant difference between painted and non-painted samples with respect to wilting point was observed at Wesleyan school, where non-painted samples were higher (**Table 3.4**). Although not significant, mean wilting points at The Westminster Schools and Holy Innocents' Episcopal School were higher for painted samples than non-painted samples, while the opposite trend was observed at Pace Academy. Similarly, Bakhshae et al. (2025) reported that microplastic contamination had minimal impact on wilting point, regardless of plastic particle size; however, this may not be true with plants that are less water resistant.

Limitations

The inconsistent trends observed for soil parameters between analyzed fields may be associated with inherent variability due to management techniques, specific sports, or construction/renovation. Fields with similar construction (soil profiles and drainage) and level of sport were chosen in order to limit variability. Soil moisture maps were also created to direct the sampling process; however, additional sensor data including surface hardness and penetration resistance may have provided further guidance. Additionally, laboratory analysis errors may have influenced experiment results. Several Tempe cells were not sealed properly, resulting in pressure leakage during laboratory evaluations. In order to rectify this, cells could have been taken apart and resealed when pressure leaks were detected; however, doing so could have damaged the samples and caused a loss of soil. Furthermore, during saturated hydraulic conductivity testing in the laboratory, the Chameleon automatic system occasionally skipped readings, which may have affected the computed average K_{sat} values. Instead of using an automatic system, the Mariotte bottle system using the constant head method could have been employed to determine K_{sat} , but this technique can also introduce human error or bias (McCarthy, 1934).

Conclusions

Although several studies have evaluated the impact of athletic field paint on plant physiology, this is the first known experiment to investigate the influence of paint presence on soil physical properties. Paint application to athletic fields may cause an increase in soil bulk density over time. Since paint is not applied uniformly across fields, this may increase surface hardness and soil compaction variability, further complicating field playability and athlete safety. Straw et al. (2018) reported a potential relationship

between ground-derived athlete injuries and surface hardness variability, with most injuries occurring in areas of transition between non-significant and significantly low and high surface hardness values. Routine aeration applications have been shown to decrease bulk density (Atkinson et al., 2012); therefore, soil cultivation methods may be required more frequently in order to reduce negative impacts of paint presence within the soil profile. Targeted or site-specific aeration may be employed on more intensively painted field locations including school logos, numbers, and endzones.

Fraise mowing is a more commonly conducted cultural practice for the removal of significant thatch layers or the reduction of annual bluegrass infestations (Aldous et al., 2014; Brosnan et al., 2020; Carroll et al., 2021). However, McCauley et al. (2025) observed that fraise mowing at deeper depths caused an increase in surface hardness. Therefore, sports fields that conduct fraise mowing may need additional aeration, especially in areas receiving high paint inputs. The use of wetting agents to alleviate poor water retention as a result of increased bulk density may be appropriate when invasive cultivation strategies cannot be employed (Karnok et al., 2004).

Acknowledgements

Thank you to Daniel Prince at Pace Academy, Jake Mays at The Westminster Schools, Nick Verrilli at Holy Innocents' Episcopal School, and Adam Culpepper at Wesleyan School and their respective grounds faculty members for allowing us to use their fields for sampling. Thank you to Pramod Hegde for aiding with R code.

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Table 3.1. Laboratory soil analysis^a for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	pH	CEC	OM	Sand	Silt	Clay	P	K	Ca	Na	Mg	Fe
	%						kg ha ⁻¹					
Pace Academy	4.96	1.78	2.26	95.9	2.06	2.08	5.6	49.2	95.6	29.1	28.9	111.1
The Westminster Schools	6.27	6.58	2.58	94.8	3.10	2.08	79.4	75.5	1179.8	29.7	64.8	126.2
Holy Innocents' Episcopal	4.89	4.16	3.62	93.8	4.14	2.08	47.3	86.2	341.3	21.2	29.8	186.2
Wesleyan School	5.47	0.46	0.56	98.8	0.14	1.08	7.9	23.6	42.8	9.6	16.1	31.3

^aA composite sample of 16 cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA.

Table 3.2. The age and annual number of paint applications for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	Age (year) ^a	Paint applications per year (approx.) ^b
Pace Academy	12	40
The Westminster Schools	14	45
Holy Innocents' Episcopal	18	25
Wesleyan School	5	25

^aThe age represents the time in years since the field was last renovated, including soil profile disturbance or replacement.

^bPainting included line markings, numbers, and aesthetic logos on each field.

Table 3.3. AICc^a values of linear mixed-effect models used to determine significance of field qualities on each soil parameter (response variable).

Model	Bulk Density	Field Capacity	Ksat	Wilting
	(g cm ⁻³) ^b	(cm ³ cm ⁻³)	(cm min ⁻¹)	Point (%)
	AICc			
y ~ (1 School)	-98.4	-119.1*	45.0*	159.5*
y ~ Treatment + (1 School)	-108.6*	-111.6	50.5	163.2
y ~ Age + (1 School)	-87.3	-109.3	47.6	161.8
y ~ PaintNumber + (1 School)	-90.1	-110.4	53.2	165.4
y ~ PaintNumber + PaintNumber:Treatment + (1 School)	-98.1	-94.7	65.9	176.3
y ~ Age + Age:Treatment + (1 School)	-85.8	-95.9	58.3	170.5
y ~ Treatment + Age + (1 School)	-97.4	-101.7	53.1	165.6
y ~ Treatment + PaintNumber + (1 School)	-100.7	-102.8	58.7	169.2
y ~ Age + PaintNumber + (1 School)	-77.8	-101.3	56.5	168.6
y ~ Treatment + Age + PaintNumber + (1 School)	-88.1	-93.7	62.1	172.6

^aAbbreviations: AICc, corrected Akaike information criterion; Ksat, saturated hydraulic conductivity.

^bField capacity and saturated hydraulic conductivity were directly measured by fitting sampling rings into a Tempe cell system while wilting point and bulk density were determined from a soil sample removed from the larger sampling ring source.

*Best model, lowest AICc value.

Table 3.4. Statistical summaries for bulk density, field capacity, saturated hydraulic conductivity, and wilting point of painted and non-painted samples retrieved from each school field.

School Name	Surface	Bulk Density (g cm^{-3}) ^a				Field Capacity ($\text{cm}^3 \text{cm}^{-3}$)			
		Min	Max	Mean ^b	SD	Min	Max	Mean	SD
Pace Academy	Painted	0.94	1.20	1.080a	0.08	0.21	0.29	0.248a	0.03
	Non-painted	0.84	1.04	1.051b	0.07	0.04	0.35	0.252a	0.11
The Westminster Schools	Painted	1.00	1.20	1.062b	0.05	0.03	0.38	0.308a	0.12
	Non-painted	0.85	1.00	1.100a	0.05	0.07	0.40	0.305b	0.10
Holy Innocents'	Painted	0.82	1.00	0.955a	0.06	0.05	0.20	0.110a	0.08
	Non-painted	0.92	1.00	0.956a	0.03	0.13	0.19	0.125a	0.02
Episcopal Wesleyan School	Painted	0.66	1.10	0.998a	0.17	0.15	0.23	0.192b	0.03
	Non-painted	0.81	1.00	0.986a	0.06	0.01	0.31	0.211a	0.10
School Name	Surface	Ksat (cm min^{-1}) ^c				Wilting Point (%)			
		Min	Max	Mean	SD	Min	Max	Mean	SD
Pace Academy	Painted	0.31	0.82	0.536a	0.19	0.68	2.7	1.646a	0.70
	Non-painted	0.04	0.62	0.449a	0.24	1.50	5.0	1.989a	1.20
The Westminster Schools	Painted	0.03	0.21	0.090b	0.06	2.80	5.1	3.653a	0.71
	Non-painted	0.04	0.77	0.106a	0.24	2.40	3.8	3.432a	0.58
Holy Innocents'	Painted	0.06	0.61	0.230a	0.18	2.90	4.1	3.396a	0.43
	Non-painted	0.01	0.36	0.213a	0.12	1.30	3.9	3.395a	0.82
Episcopal Wesleyan School	Painted	0.02	1.75	0.783a	0.35	0.58	1.8	1.282b	0.42
	Non-painted	0.26	1.31	0.740a	0.61	1.30	2.0	1.380a	0.28

^aField capacity and saturated hydraulic conductivity were directly measured by fitting sampling rings into a Tempe cell system while wilting point and bulk density were determined from a soil sample removed from the larger sampling ring source.

^bMeans for all parameters are based off of 16 samples obtained throughout each field.

^cAbbreviations: Ksat, saturated hydraulic conductivity.

CHAPTER 4
IMPACT OF ATHLETIC FIELD PAINTING ON ATHLETE BIOMECHANICS AND
PERENNIAL RYEGRASS (*Lolium perenne* L.) SEED GERMINATION

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Abstract

Many natural turfgrass sports fields receive subsequent applications of athletic paint throughout a sporting season. This practice is commonly performed to provide boundary lines and aesthetics for athletes and spectators. However, paint components, specifically pigments, may inhibit photosynthetic activity and cause a decrease in turfgrass quality. Player-surface interaction research concluded that athletes have higher injury risk when traveling between areas of satisfactory and unsatisfactory turfgrass quality. Therefore, the objective of this study was to determine if the presence of athletic field paint affects perennial ryegrass (*Lolium perenne* L.) germination and athlete biomechanics. A germination experiment was conducted with soil cores from painted and non-painted areas of four natural turfgrass sports fields built to USGA specifications in the Metro Atlanta area in GA. Cores were transported to a greenhouse in Athens, GA, seeded with 'Champion GQ' perennial ryegrass, and allowed to germinate over four weeks. Athlete biomechanics were studied using two running lanes of overseeded bermudagrass, one painted and one non-painted. Ten active, college-aged females were recruited to perform two maneuvers on each running lane, a single-leg cut and a modified acceleration/deceleration activity. Inertial measurement units were placed on participants to record peak vertical and horizontal tibial accelerations (vTA and hTA, respectively) and peak knee flexion angles. Athlete perceptions were recorded after activities to further explain surface interactions. The only significant difference observed in germination was in the first 2.1 cm section of the Wesleyan School intact soil cores (48% painted, 73% non-painted); however, two of the four schools showed trends of reduced ryegrass germination in painted cores, although not significant. For the single-let cut activity,

significant differences were only seen in the peak vTA ($94.92 \pm 19.47 \text{ m s}^{-2}$ on the non-painted running lane and $116.90 \pm 7.26 \text{ m s}^{-2}$ on the painted running lane). While there were no significant differences, higher peak hTA were observed across participants on the non-painted surface during the modified acceleration/deceleration activity. When asked about preferences, athletes generally liked the painted surface due to a perceived ability to grip and make easier cuts.

Introduction

Natural turfgrass sports fields are subjected to exorbitant amounts of wear and traffic that require significant management inputs in order to recover and maintain an adequate playing surface throughout the season. Athletic paint is often used to help display sport specific boundary lines and provide aesthetic logos within the playing field. Most paints are water-based latex that contain additional ingredients such as pigments, resins, solvents, and additives (Reynolds et al., 2012). Each of these components may affect plant and soil parameters differently; however, pigments are especially problematic since they often cover turfgrass leaves for an extensive period of time. Since paint can be applied at different carrier volumes and through diverse methods, such as rollers or aerosol cans, application technique may influence paint deposition on the leaf surface. Reynolds et al. (2012) reported a reduction in canopy photosynthesis as paint application events increased, closely mimicking shade stress. Although some species are more tolerant of reductions in photosynthesis, decreases in turfgrass quality are often observed after a week of shade conditions (Baldwin et al., 2009). Declines in field quality may increase the variability of several soil and plant parameters, causing a shift in athlete

perception and adjustments in their behavior when playing on these surfaces (Straw et al., 2019). Furthermore, greater athlete injury occurrence has been documented in areas of transition between non-significant and significantly low and high turfgrass quality (Straw et al., 2018).

Overseeding is a common cultural practice intended to increase canopy uniformity and enhance the shear strength of dormant warm-season turfgrass sports fields in the southeastern U.S. during the fall and winter. Perennial ryegrass (*Lolium perenne* L.) and annual ryegrass (*L. multifloram* Lam.) are the most widely utilized species for overseeding due to quick germination and wear/traffic tolerance (Mazur & Rice, 1999; Pornaro et al., 2024). However, several environmental factors including soil moisture, temperature, and light intensity affect the establishment of turfgrass species, including ryegrass (Aronson et al., 1987; Shin et al., 2006). The presence of shade, which often exists due to trees or stadium obstructions, may reduce ryegrass germination and overall stand density/quality (Gardner & Taylor, 2002). Athletic field paint applications to the turfgrass canopy may reduce light infiltration to the soil surface, while the presence of paint in the soil profile may alter soil physical properties like wilting point and field capacity making establishment even more difficult.

Variability that exists within sports fields may reduce surface predictability or cause athletes to make abrupt or frequent adjustments, leading to a higher risk for injury. Athletic field paint is applied non-uniformly, further creating surface variability. Previous research examining player-surface interactions has been in situ and no one has examined the response of athletes to painted turfgrass surfaces. The recent introduction of wearable inertial measurement units (IMUs) allows for the generation of athlete kinetic and

kinematic data in real time. These units typically contain a gyroscope, accelerometer, and magnetic sensors in order to determine their location in space while collecting angular velocities or accelerations (Camomilla et al., 2018; Burbrink et al., 2023). Begitschke (2025) reported differences in knee flexion angles using wearable IMU sensors when athletes performed prescribed maneuvers on a variety of surfaces. If an athlete experiences lower knee flexion angles when interacting with a playing surface, they will have a greater risk of injury occurrence (Leppänen et al., 2017). Therefore, the objectives of our research were to determine the effect of athletic field paint on perennial ryegrass germination and the interaction between players and painted turfgrass surfaces using wearable IMU sensors. Athlete perceptions of different surfaces will also be recorded following player-surface interactions.

Materials and Methods

Ryegrass Germination

Research was conducted in the summer of 2024 at four natural grass sports fields located throughout the Metro Atlanta area in GA. Locations included Pace Academy in Mableton, GA (33.8497° N, 84.4171° W), The Westminster Schools in Atlanta, GA (33.8419° N, 84.4341° W), Holy Innocents' Episcopal School in Atlanta, GA (33.9078° N, 84.4152° W), and Wesleyan School in Peachtree Corners, GA (33.9713° N, 84.2165° W). Fields measured 48.8 m x 109.7 m and were primarily used for varsity level sports including American football, soccer, and lacrosse. No renovation was conducted within the past five years and all fields were surfaced with hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy]. The hybrid bermudagrass cultivars at each location were as follows: 'Tifway' at Pace Academy, The Westminster Schools, and

Holy Innocents' Episcopal School; 'TifTuf' at Wesleyan School. Perennial ryegrass (*Lolium perenne* L.) was overseeded on each field yearly at a rate of 391 to 586 kg ha⁻¹ in the fall. Each field was constructed to United States Golf Association (USGA) specifications with a 31 to 41-cm depth sand rootzone (9:1 sand to peat mixture) placed above a 10-cm gravel layer with a drainage system installed below for the removal of excess water. Management practices for all locations included weekly irrigation at approximately 2.5 cm wk⁻¹ and regular painting of field boundary lines and school logos. A composite sample of 16 soil cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field, air-dried for 48 hours, sieved through a 2-mm mesh screen, and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA for analysis (**Table 4.1**). Field ages (since last renovation) and number of painting applications per year are presented in **Table 4.2**.

Sample Collection

Volumetric water content (%VWC) maps were created to guide sampling areas in the field in order to account for underlying conditions related to soil moisture. A FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL) was utilized to record %VWC measurements (an average of three readings) on a 9 x 9 m grid. Readings were georeferenced with a Trimble GPS unit. Soil moisture (%VWC) data was analyzed with ArcGIS Pro version 3.2.0 (ESRI, Redlands, CA). Soil moisture data based on the observed range of values in our four fields were interpolated using the inverse distance weighting (IDW) method to create continuous raster maps.

The soil moisture range in which samples were collected at each location were as follows: 20-30 %VWC at Pace Academy and Wesleyan School, 40-45 %VWC at The

Westminster Schools, and 12-25 %VWC at Holy Innocents' Episcopal School. Soil sample locations were based on %VWC in order to help reduce sample variability. Eight non-painted and eight painted samples were collected with a bulk density sampler and slide hammer attachment (15.2 cm height and 5.1 cm diameter, AMS, Inc., American Falls, ID) from each field.

Soil cores were transported to the Athens Turfgrass Research and Education Center greenhouse complex in order to evaluate the germination of 'Champion[®] GQ' perennial ryegrass (90% germination potential) (Seed Research of Oregon by DLF, Albany OR). The greenhouse was maintained at 30/24°C (day/night) with average midday (1200 and 1300 hr) solar radiation ranging from 636 to 754 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Supplemental lighting (350 $\mu\text{mol m}^{-2} \text{s}^{-1}$) was provided with metal halide lamps (1000 W) to simulate a 16-h day length. Irrigation was supplied through an overhead irrigation system calibrated to deliver approximately 3.8 cm of water wk^{-1} . No fertilizer was applied to the soil cores during the trial. Perennial ryegrass seeds were planted on the following three soil core components:

1. Thatch disk: Above-ground biomass plus the thatch layer was removed from the remaining soil core at the soil surface interface. The disk was inverted and placed thatch side up on a tray. Ten perennial ryegrass seeds were evenly distributed over the thatch surface.
2. Soil surface disk: A second disk was removed to a depth of 1.3 cm from the remaining intact soil core to simulate fraise mowing. Ten perennial ryegrass seeds were evenly distributed over the soil surface.

3. Soil core: The remaining intact soil core (6.3 cm) was planted with 30 perennial ryegrass seed by making a shallow furrow and placing the seed down the length of the entire soil core.

All soil core components were placed in trays separated by school and arranged in a randomized complete block design. Experimental blocks were arranged along a gradient created by the greenhouse cooling pads and associated fans. Seeds were allowed to germinate over a four week period. Percent germination was collected for the thatch and soil surface disks by counting the number of seedlings present and dividing by the number of seeds planted. The remaining intact soil core was subdivided into three equal lengths (2.1 cm each). Percent germination was calculated the same as above and presented as three separate numbers based on depth location within the soil core.

Athlete Biomechanics and Perceptions

Plot Establishment

Running lane plots (1.5 m x 12.2 m) of overseeded 'IronCutter' hybrid bermudagrass and painted overseeded hybrid bermudagrass were established at the Athens Turfgrass Research and Education Center in Athens, GA (33° 54' 19.7892" N, 83° 22' 26.1228" W) during the fall of 2024. Each running lane was divided into two equal 1.5 m × 6.1 m plots for analysis. All running lanes were established on a native Pacolet sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults) soil (68% sand, 10% silt, 22% clay, 3.9% organic matter, 5.4 pH, per soil test results from the University of Georgia Agricultural and Environmental Services Laboratory). Prior to overseeding, dormant hybrid bermudagrass plots were scalped to 1.8 cm (clipping biomass removed) before overseeding with 'Champion GQ' perennial ryegrass. Overseeding was conducted

on October 2, 2024 with a drop spreader calibrated to apply 9.8 g seed m⁻² per pass. Five total passes were made in different directions in order to uniformly apply a total of 49 g seed m⁻² across the dormant hybrid bermudagrass plots. All seeded plots received a light topdressing (0.25 cm) of medium-textured (0.25 - 0.5 mm) sand (Pallas Landscape Supply, Athens, GA) following seeding to promote seed-to-soil contact. Plots were maintained at 2 cm throughout the duration of the trial with a Toro Greensmaster 1600 walk-behind reel mower (The Toro Company, Bloomington, MN) with clippings collected. Irrigation was applied with an overhead system to supplement natural rainfall for a total of approximately 3.2 cm wk⁻¹. All overseeded hybrid bermudagrass plots received 24.4 kg N ha⁻¹ (18-12-6 Nutrite Professional Turf fertilizer, Pro Turf Grade; Phoenix, AZ) on October 16, 2024 and another 24.4 kg N ha⁻¹ (25-0-3 The Anderson's fertilizer; Maumee, OH) on November 15, 2024. Four days prior to trial initiation, sports field paint (Pioneer Athletics, Cleveland, OH) was applied with rollers to the entire area of one running lane (1.5 m x 12.2 m).

Athlete Biomechanics and Perceptions

Research was conducted on the same running lane plots described above in order to determine the effect of paint presence on player lower-limb kinetics and kinematics during athletic maneuvers on hybrid bermudagrass. The University of Georgia Institutional Review Board (ID: PROJECT00009189) granted approval to conduct human participant research utilizing the following methodology and data collection.

Ten active female college-aged participants were recruited to perform three trials of two athletic activities on each running lane (**Table 4.3**). Participants were pre-screened prior to selection to determine eligibility based on the following requirements:

- Participants must have been between 18-30 years old
- Participants must have participated in 30 minutes or more of moderate to vigorous physical activity at least 3 times per week (per American College of Sports Medicine physical activity guidelines)
- Participants must not have had any history of muscle, ligament, or tendon injuries in the previous three months that resulted in greater than 24 hours of time-loss from physical activity
- Participants must not have had any orthopedic surgeries within the previous year

Each participant completed one testing session from November 22 - 26, 2024. Shear strength and volumetric water content were measured immediately prior to any testing session using the Turf-Tec Shear Strength Tester TSHEAR2-M (Turf-Tec International, Tallahassee, FL) and the FieldScout TDR300, respectively. Means of these parameters for each running lane per testing session are presented in **Table 4.4**. The experimental design was a repeated measures design with ten replications/participants and surface being the main effect.

Participants were fitted with three calibrated Vicon® Blue Trident® (Vicon Motion System, Denver, CO) IMU sensors, one on the posterior pelvis, one on the lateral thigh of the dominant leg aligned with the femur (located at the femoral midpoint, or halfway between the knee joint and hip joint), and one on the lateral shank of the dominant leg aligned with the tibia (located at the tibial midpoint, or halfway between the ankle joint and knee joint). The dominant leg was determined during consultation prior to the start of the session and was defined as whichever foot was primarily used to kick a soccer ball. The Blue Trident IMUs contain two accelerometers (± 16 g at 1125 Hz and ± 200 g at

1600 Hz), a magnetometer ($\pm 4900 \mu\text{T}$ at 112 Hz), and a gyroscope ($\pm 2000^\circ \text{ s}^{-1}$ at 1125 Hz; Lesinski et al., 2018). The IMUs were secured to the participants by first covering the area with self-adhesive wrap, then attaching the IMUs to the self-adhesive wrap via double-sided tape, and finally securing the IMU with additional athletic tape. Once fitted with IMUs, participants were instructed to complete a calibration pose, which was defined as standing still with their feet shoulder width apart and hands by their side, to calibrate the IMUs to each participant's individual skeletal structure.

Participants were instructed to wear their own cleats to allow for natural movement during the trial (**Table 4.3**). Once the IMUs were fitted and calibrated, participants completed a self-guided warm-up procedure for approximately 10 minutes before completing the following athletic activities on each surface:

1. Three replications of a single-leg cut landing (SLC), where participants stepped off a 30-cm platform with their dominant foot and immediately cut at 45° in the opposite direction of their dominant leg (cut to the left off their right foot for a right-leg dominant participant) and accelerated for a short distance. Each replication was completed in a different location down the length of each running lane to avoid excessive turfgrass wear and soil compaction.
2. Three replications of a modified acceleration-deceleration (AD), where upon receiving a "Go" command by the research team, participants accelerated 20 m at maximum effort before decelerating at maximum effort into a backpedal. Start/stop locations were rotated for each replication to avoid excessive turfgrass wear and soil compaction.

These activities were chosen to replicate a natural cutting and sprinting movement experienced on an athletic field, and are commonly used for biomechanics research (Lesinski et al., 2018; Harper et al., 2023). The order of activities was consistent with each participant (3 replications of SLC, then 3 replications of the AD); however, the order of the two evaluated surfaces was randomized for each participant. Regions of interest were created for each replication of each activity within the IMU software (Capture.U 1.4.1; Vicon Motion System, Denver, CO) on a 10th generation iPad (Apple; Cupertino, CA) that connects to the IMUs via Bluetooth to allow for data processing and analysis.

Upon completion of the testing session, participants had the option to answer a brief series of survey questions in a conversational manner to gather participants' perceptions of each surface (**Table 4.5 and 4.6**). The questions were as follows:

1. Which surface did you like the best? Why?
2. Rank the surfaces based on which felt the most stable.
3. Rank the surfaces based on which felt the hardest.
4. Which surface would you prefer to play on? Why?

Data from these survey questions were compared to the objectively measured surface characteristic and biomechanical data to determine if the participants' perceptions matched the objectively measured data. For the ranking questions (questions 2 and 3), numerical values were placed on the metrics so that 1 was the softest/least stable surface and 2 was the hardest/most stable surface. The sums of the values are shown in **Table 4.7** and used for comparison between surfaces, with the highest sums indicating the hardest/most stable surface.

Data Analysis

Ryegrass Germination

Percent germination for the thatch disk, soil surface disk, and all three intact soil core subdivisions were subjected to a one-way analysis of variance ($\alpha = 0.05$) in R[®] version 4.3.2. Lowercase letters were utilized to depict statistical differences between perennial ryegrass germination means when appropriate.

Athlete Biomechanics

Aligned data from the IMUs were extracted and evaluated for peak tibial accelerations and peak knee flexion angles experienced by each participant during each athletic maneuver. The raw ± 200 g acceleration data measured by the tibial IMU for each activity for each participant was filtered using a Butterworth fourth-order zero-phase shift filter with a cutoff frequency of 50 Hz using the “butfilt_vbz_xla_v2.xla” add-in (created by: Sam Van Wassenbergh, University of Antwerp, June 6, 2007 in ‘Microsoft Visual Basic for Applications’ for Microsoft Excel 2000; Erer, 2007; Winter, 2009) within Microsoft Excel (Microsoft Corporation, Redmond, WA). Once filtered, the peak tibial accelerations were extracted from the vertical plane (x -axis of tibial IMU; vTA) and horizontal plane (magnitude of the y - and z -axes of the tibial IMU; hTA) for analysis. The peak vTA and hTA experienced during the initial footstrike of the “cutting” motion of the SLC and AD activity (**Table 4.8 and Table 4.9**, respectively) were isolated and extracted for analysis. A significant participant \times surface interaction was detected for each parameter; therefore, data for each participant were analyzed and presented separately.

The aligned data from all three IMUs downloaded from the Capture.U IMU software were further imported into the OpenSense[®] processing executable GUI (Vicon

Motion System, Centennial, CO 80112) within the OpenSim[®] human modeling software (Delp et al., 2007) to calculate reverse kinematic data during each activity. Due to processing limitations of the OpenSense[®] software, the aligned IMU data was extracted from the Capture.U IMU software at 50 Hz to determine peak knee flexion during each trial. Peak knee flexion angles during initial footstrike of the “cutting” motion of the SLC (**Table 4.8**) was isolated and extracted from the OpenSense[®] processing output for analysis. For the SLC activity, the start of each trial was indicated by the first peak in vTA data $> 50 \text{ m s}^{-1} \text{ s}^{-2}$ observed, which indicated the first “cutting” footstrike. The peak knee angle that immediately followed that initial peak in vTA was extracted for analysis.

Both the peak tibial acceleration and peak knee flexion angle data were averaged across athletes and subjected to analysis of variance ($\alpha = 0.05$) in R[®] version 4.3.2. To analyze the difference between surfaces, Cohen’s d was performed to determine effect size.

Results and Discussion

Ryegrass Germination

No significant differences were observed in perennial ryegrass germination between painted and non-painted thatch disks or surface disks, regardless of school (**Table 4.10**). The only significant difference detected within painted and non-painted intact soil cores was noted in the first 2.1 cm core subdivision for Wesleyan School (48% painted, 73% non-painted). Although not significant, perennial ryegrass germination was greater for all non-painted intact soil cores and surface disks at Holy Innocent’s Episcopal School and The Westminster Schools, but lower for non-painted thatch surfaces. Zhu et al. (2018) reported a reduction in germination of 65 grass species ranging

from 4.3% to 100% when established in the presence of crude oil. More specifically, perennial ryegrass germination was reduced 38% when seeded into a contaminated sandy loam soil (Zhu et al., 2018). Similarly, several researchers have observed a reduction in perennial ryegrass germination (25% to 51%) in the presence of drilling waste which often contains lubricating chemicals, hydrocarbons, heavy metals, and water-soluble salts (Zhu et al., 2019; Gawryluk et al., 2022). Although the components of athletic field paint (pigments, resins, solvents, and additives) and their toxicology are very different than crude oil and drill waste, the presence of these materials within the soil profile may have a similar impact on soil physical properties and subsequent perennial ryegrass germination.

Athlete Biomechanics

Although not statistically analyzed, recorded means for shear strength and soil moisture were slightly higher on the painted running lane for all testing sessions (**Table 4.4**).

Single-Leg Cut Activity

Average vertical tibial accelerations across all participants for non-painted and painted surfaces were significantly different and show a moderate effect size ($94.92 \pm 19.47 \text{ m s}^{-2}$ on the non-painted running lane and $116.90 \pm 7.26 \text{ m s}^{-2}$ on the painted running lane, Cohen's d of -0.61 and -0.22, respectively; **Table 4.11**) during the single-leg cut activity. However, the horizontal tibial accelerations and knee angles were not significantly different and encountered small effect sizes across participants between the non-painted and painted surfaces (**Table 4.11**). The majority of athlete participants (8/10) experienced higher average peak vTA and peak hTA on the painted surface (**Table**

4.8). Half of the participants exhibited higher knee angles on the painted surface while the other half exhibited higher knee angles on the non-painted surface (**Table 4.8**).

Modified Acceleration/Deceleration Activity

No significant differences and a small effect size between painted and non-painted surfaces were observed for both average vertical and horizontal tibial accelerations during the modified acceleration/deceleration activity (**Table 4.12**). It is of note that all participants experienced higher peak hTA on the non-painted surface while five participants had higher peak vTA on the non-painted surface (**Table 4.9**). Milner et al. (2006) hypothesized that higher tibial accelerations were associated with tibial stress fractures. Harder surfaces can also lead to this type of injury; therefore, it is inferred that non-painted running lanes are firmer than painted surfaces (Behrens et al., 2013).

While previous research has examined the interaction between athletes and a variety of surfaces (natural grass, synthetic turf, acrylic and clay courts, etc.), no research has ever examined the response of players to painted turfgrass (Taylor et al., 2012; Starbuck et al., 2016; Straw et al., 2018). However, Curry et al. (2007) utilized a Brungraber MkII Portable Inclined Articulated Strut Tester to measure the slip resistance of marking paints (waterborne latex, waterborne acrylic, and solvent-based alkyd) applied to different surface types (brushed concrete, very smooth concrete, and asphalt). The addition of paint did not reduce the slip resistance on any of the surfaces, but resulted in a substantial increase in slip resistance, even under wet conditions (Curry et al., 2007). The authors theorized that the solid ingredients (binders and pigments) that remain after the evaporation of liquid fractions following application create a film on the

surface that increases friction. A similar phenomenon may have occurred with the application of athletic field paint to the turfgrass canopy in our research.

Athlete Perceptions

Although tibial acceleration and knee angle data provide insight into athlete interactions with the different surfaces, participant perceptions allow for a deeper understanding about their experience during the interaction and potential considerations for future interactions. Six out of ten participants preferred the painted surface, three preferred the non-painted surface, and one had no preference (**Table 4.5**). Athletes often described the surface that they selected as feeling “softer” or attributed their selection to the surface with “more traction” or “grip”, regardless of choice.

When asked which surface athletes preferred to play on, seven out of ten chose the painted surface, two preferred the non-painted surface, and one had no preference (**Table 4.6**). Athletes that preferred the painted surface gave reasons similar to the previous question. Most participants said that the surface felt like it had more grip or traction and allowed for easier performance of the cutting motion maneuver. One participant said that she liked the painted surface better because it felt similar to surfaces in which she previously played (i.e., synthetic turf systems).

The painted running lane was generally perceived as the hardest and most stable when participants were asked to rank the surfaces (**Table 4.7**). However, some participants were not able to distinguish between the two running lanes. Furthermore, the horizontal tibial accelerations that were obtained during the modified acceleration/deceleration activity indicated that the non-painted lane may be the harder of the two surfaces. The fact that this was not reflected in the perception ranking answers is

further evidence that surface hardness measurements should have been recorded to more accurately quantify this parameter. Although conducted on tennis courts, greater initial knee flexion and a more upright position was reported on clay versus acrylic courts, suggesting player adaptation on clay to increase stability (Starbuck et al., 2016). Player perception data generated through a visual analogue scale questionnaire confirmed that all participants perceived the differences in surface properties between the clay and acrylic courts and thus responded appropriately to these differences.

Limitations and Conclusions

Methods utilized in the perennial ryegrass germination study may have impacted the results. Javaid et al. (2022) reported that the optimal temperature for maximum perennial ryegrass germination (95%) was 25°C; however, we conducted our germination study in a greenhouse set to 30/24°C (day/night). Perennial ryegrass germination at 30°C, although statistically similar, was approximately 10 to 12% less with substantial reductions in root and shoot biomass (Javaid et al., 2022). An increase in perennial ryegrass germination in our research may have resulted if soil cores were maintained at 25°C; however, it is unclear how that would have impacted painted versus non-painted treatments. Soil analysis differences of the four sampled fields may have revealed additional influences on the perennial ryegrass germination study. Javaid et al. (2022) noted a decrease in perennial ryegrass germination as sodium levels increased. Some of the highest germination percentages in our research were observed in the intact soil cores of Wesleyan School, which also exhibited the lowest sodium levels (9.6 kg ha⁻¹) compared to the other three schools (21.2 to 29.7 kg ha⁻¹), potentially affecting the trial results.

The trial conditions implemented in the athlete biomechanics and perception research may not be indicative of real-world conditions. Sports fields typically receive 25-45 paint applications per year (**Table 4.2**); however, running lanes in our research were only painted once before athletes traversed the surface. The addition of subsequent paint applications may have influenced resultant acceleration/deceleration and knee flexion angles. Running lanes were established on a native soil (sandy clay loam); therefore, paint distribution typically observed throughout a USGA-spec sand-based profile may have been limited, potentially altering player-surface interactions. Finally, although participants were all females, selecting athletes who played the same sport or possessed similar athletic skill may have reduced potential variability in trial results.

Although minimal statistical significance was detected among treatments, regardless of school, a reduction in perennial ryegrass germination was observed in soil cores containing the presence of paint for several sampled fields. However, inherent differences in soil analysis between fields may have influenced the results. More participants preferred to interact with painted surfaces due to the perception of enhanced footing or grip when conducting athletic maneuvers, but variability in skill level may have reduced our ability to detect differences in player-to-surface interactions between the two surfaces. Future research could examine in situ evaluations of painted surfaces or controlled environment experiments that reduce inconsistencies in methodology.

Acknowledgements

Thank you to Daniel Prince at Pace Academy, Jake Mays at The Westminster Schools, Nick Verrilli at Holy Innocents' Episcopal School, and Adam Culpepper at

Wesleyan School for allowing our team to take field samples. Thank you to all our student athletes who made time to participate in this research.

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Table 4.1. Laboratory soil analysis^a for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	pH	CEC	OM	Sand	Silt	Clay	P	K	Ca	Na	Mg	Fe
				%			kg ha ⁻¹					
Pace Academy	4.96	1.78	2.26	95.9	2.06	2.08	5.6	49.2	95.6	29.1	28.9	111.1
The Westminster Schools	6.27	6.58	2.58	94.8	3.10	2.08	79.4	75.5	1179.8	29.7	64.8	126.2
Holy Innocents' Episcopal	4.89	4.16	3.62	93.8	4.14	2.08	47.3	86.2	341.3	21.2	29.8	186.2
Wesleyan School	5.47	0.46	0.56	98.8	0.14	1.08	7.9	23.6	42.8	9.6	16.1	31.3

^aA composite sample of 16 cores (four 2.5-cm diameter soil cores to a depth of 12.7 cm) were obtained across each field and sent to the University of Georgia Agricultural and Environmental Services Laboratories in Athens, GA.

Table 4.2. The age and annual number of paint applications for the four high schools sampled throughout the Metro Atlanta area in GA.

School Name	Age (year) ^a	Paint applications per year (approx.) ^b
Pace Academy	12	40
The Westminster Schools	14	45
Holy Innocents' Episcopal	18	25
Wesleyan School	5	25

^aThe age represents the time in years since the field was last renovated, including soil profile disturbance or replacement.

^bPainting included line markings, numbers, and aesthetic logos on each field.

Table 4.3. Demographic information of the ten active, college-aged participants that were recruited to perform one trial of two athletic activities on each running lane.

Participant ^a	Age	Height (cm)	Mass (kg)	Cleat type	Dominant Foot
1	22	163	53.5	Soccer	Right
2	24	152	59.4	Baseball/Softball	Right
3	20	163	58.9	Soccer	Right
4	30	160	62	Baseball/Softball	Right
5	20	165	61.7	Lacrosse	Left
6	24	163	58.9	Soccer	Right
7	27	157	59.9	Baseball/Softball	Right
8	24	170	64.1	Soccer	Right
9	23	152	46.3	Soccer	Right
10	20	160	61.2	Soccer	Right

^aParticipants are listed in order of when they performed their testing session.

Table 4.4. Average shear strength^a and soil moisture^b for each running lane measured immediately before participants interacted with each surface during the testing session.

Date	Participants	Surface	Shear strength	Soil moisture
			Nm	% VWC
11/22/2024	1, 2, 3	Painted	23.75	20.8
		Non-painted	20.75	20.3
11/25/2024	4, 5, 6, 7, 8, 9	Painted	22.25	18.4
		Non-painted	21.88	17.1
11/26/2024	10	Painted	23.25	24.6
		Non-painted	20.63	23.9

^aShear strength was measured using the Turf-Tec Shear Strength Tester which determines the rotational force required to tear the turfgrass. The highest torque (Nm) measurement determined using the torque wrench handle during the turning motion for each plot was recorded.

^bSoil moisture was measured using a FieldScout TDR 300 Soil Moisture Meter with two 5 mm diameter, 7.6 cm depth stainless steel probes spaced 3.3 cm apart that are inserted into the soil to measure percent volumetric water content (%VWC).

Table 4.5. Participant responses to the first survey question: “Which surface did you like the best? Why?” The question was asked in a conversational manner at the conclusion of each testing session and responses were noted by the research team.

Participant	Most-liked Surface	Reason
1	Painted	Feels softer
2	Painted	Felt like it had more traction
3	Painted	More like what she’s used to playing on and has more grip
4	No preference	n/a
5	Non-painted	No mental blocks
6	Non-painted	Felt like her feet “gripped” better
7	Painted	Felt like it was softer
8	Non-painted	Enjoyed running on it better and felt softer
9	Painted	Felt easier to run on and could get her feet off the ground faster
10	Painted	Felt like it had more traction

Table 4.6. Participant responses to the fourth survey question: “Which surface would you prefer to play on? Why?”. The question was asked in a conversational manner at the conclusion of each testing session and responses were noted by the research team.

Participant	Preferred Surface	Reason
1	Painted	Felt more like “real grass” and doesn’t usually want to land on hard surfaces
2	Painted	Had more grip
3	Painted	Cleats were able to get more friction
4	Non-painted	Paint seemed to transfer onto her cleats
5	Painted	Closer to what she’s used to playing on (synthetic turf) and more stable
6	Painted	Surface felt more even and gives her more agility
7	No preference	Getting more traction during play is the most important aspect for her
8	Non-painted	Felt that she had more control when running
9	Painted	Felt like she could run faster on this surface because it was more “bouncy” and smoother
10	Painted	Felt like she could cut easier

Table 4.7. Participant responses to the second and third ranked survey questions: “Rank the surfaces based on which felt the most stable” and “Rank the surfaces based on which felt the hardest.” For each metric, the answers are ranked with 1 being softest/least stable and 2 being hardest/most stable. The questions were asked in a conversational manner at the conclusion of each testing session and responses were noted by the research team.

Participant	Perceived surface hardness		Perceived surface stability	
	Painted	Non-painted	Painted	Non-painted
1	1	2	2	1
2	1	2	2	1
3	2	1	2	1
4	No difference		No difference	
5	No difference		2	1
6	2	1	2	1
7	No difference		2	1
8	2	1	1	2
9	2	1	2	1
10	2	1	2	1
Sum	12	9	17	10

Table 4.8. Peak vertical tibial acceleration (vTA), horizontal tibial acceleration (hTA), and knee flexion angle measured by the tibial IMU experienced by each participant during the initial footstrike of the single-leg cut (SLC) activity.

Surface	Participants									
	1	2	3	4	5	6	7	8	9	10
	-----vTA ($\text{m s}^{-1} \text{s}^{-2}$)-----									
Non-painted	105.39	91.65	79.17	94.10	69.37	73.91	94.44	98.37	104.98	137.77
Painted	85.83	242.78	138.10	111.36	122.93	125.88	70.75	98.66	140.45	149.17
	-----hTA ($\text{m s}^{-1} \text{s}^{-2}$)-----									
Non-painted	56.02	35.44	38.69	75.74	36.90	47.46	46.59	42.75	49.08	47.09
Painted	43.03	71.90	53.98	88.33	61.67	47.87	50.35	39.83	58.19	49.74
	-----Knee Angle ($^{\circ}$)-----									
Non-painted	48.95	45.12	54.83	51.63	47.34	46.78	63.47	63.39	61.36	61.74
Painted	53.72	41.78	60.05	59.76	41.53	49.52	67.12	57.72	55.49	59.45

Table 4.9. Maximum peak vertical tibial acceleration (vTA) and horizontal tibial acceleration (hTA) measured by the tibial IMU experienced by each participant during the modified acceleration/deceleration (AD) activity.

Surface	Participants									
	1	2	3	4	5	6	7	8	9	10
	-----vTA (m s ⁻¹ s ⁻²)-----									
Non-painted	360.08	197.01	225.50	197.76	216.42	245.49	155.80	128.87	207.37	269.72
Painted	363.51	204.90	206.95	192.69	231.93	240.31	182.26	147.29	155.20	206.83
	-----hTA (m s ⁻¹ s ⁻²)-----									
Non-painted	122.49	283.33	101.13	112.53	253.15	268.53	137.57	110.01	101.77	201.66
Painted	95.01	277.92	87.35	80.78	237.39	265.89	137.07	80.71	100.31	179.98

Table 4.10. Average values of percent germination for painted and non-painted areas at each school.

School		Thatch	Disk	2.1 cm	4.2 cm	6.3 cm
		-----% germination-----				
Holy Innocents' Episcopal School	Painted	31 ^{NS}	65 ^{NS}	34 ^{NS}	51 ^{NS}	58 ^{NS}
	Non-painted	26 ^{NS}	71 ^{NS}	50 ^{NS}	56 ^{NS}	60 ^{NS}
Pace Academy	Painted	15 ^{NS}	65 ^{NS}	54 ^{NS}	58 ^{NS}	36 ^{NS}
	Non-painted	14 ^{NS}	65 ^{NS}	38 ^{NS}	43 ^{NS}	32 ^{NS}
The Westminster Schools	Painted	68 ^{NS}	39 ^{NS}	46 ^{NS}	53 ^{NS}	66 ^{NS}
	Non-painted	64 ^{NS}	44 ^{NS}	61 ^{NS}	66 ^{NS}	70 ^{NS}
Wesleyan School	Painted	54 ^{NS}	68	48 ^{b^a}	71 ^{NS}	78 ^{NS}
	Non-painted	48 ^{NS}	60	73 ^a	74 ^{NS}	66 ^{NS}

^{NS}, Nonsignificant

^aMeans with different letters within the same column are significantly different at the $\alpha = 0.05$ significance level.

Table 4.11. Overall mean and standard deviations across all participants for vertical acceleration, horizontal acceleration, and knee angle for the single-leg cut (SLC) activity.

Surface	vTA (SD)	hTA (SD)	Knee Angle (SD)
	----- m s ⁻¹ s ⁻² -----		Degrees (°)
Non-painted	94.92b ^a (19.47)	47.58a (11.70)	54.5a (7.43)
Painted	116.90a (7.26)	56.49a (56.49)	54.6a (8.22)
Cohen's d	-0.61	-0.22	-0.02

^aMeans with the same letters within the same column are not significantly different at the $\alpha = 0.05$ significance level.

Table 4.12. Overall mean and standard deviations across all participants for vertical acceleration and horizontal acceleration for the acceleration/deceleration (AD) activity.

Surface	vTA (SD)	hTA (SD)
	----- m s ⁻¹ s ⁻² -----	
Non-painted	220.40 ^a (63.59)	169.22 ^a (74.59)
Painted	213.19 ^a (60.48)	154.24 ^a (79.81)
Cohen's d	0.12	0.19

^aMeans with the same letters within the same column are not significantly different at the $\alpha = 0.05$ significance level.

APPENDIX A
SPATIAL COMPARISON SUPPLEMENTAL MATERIAL

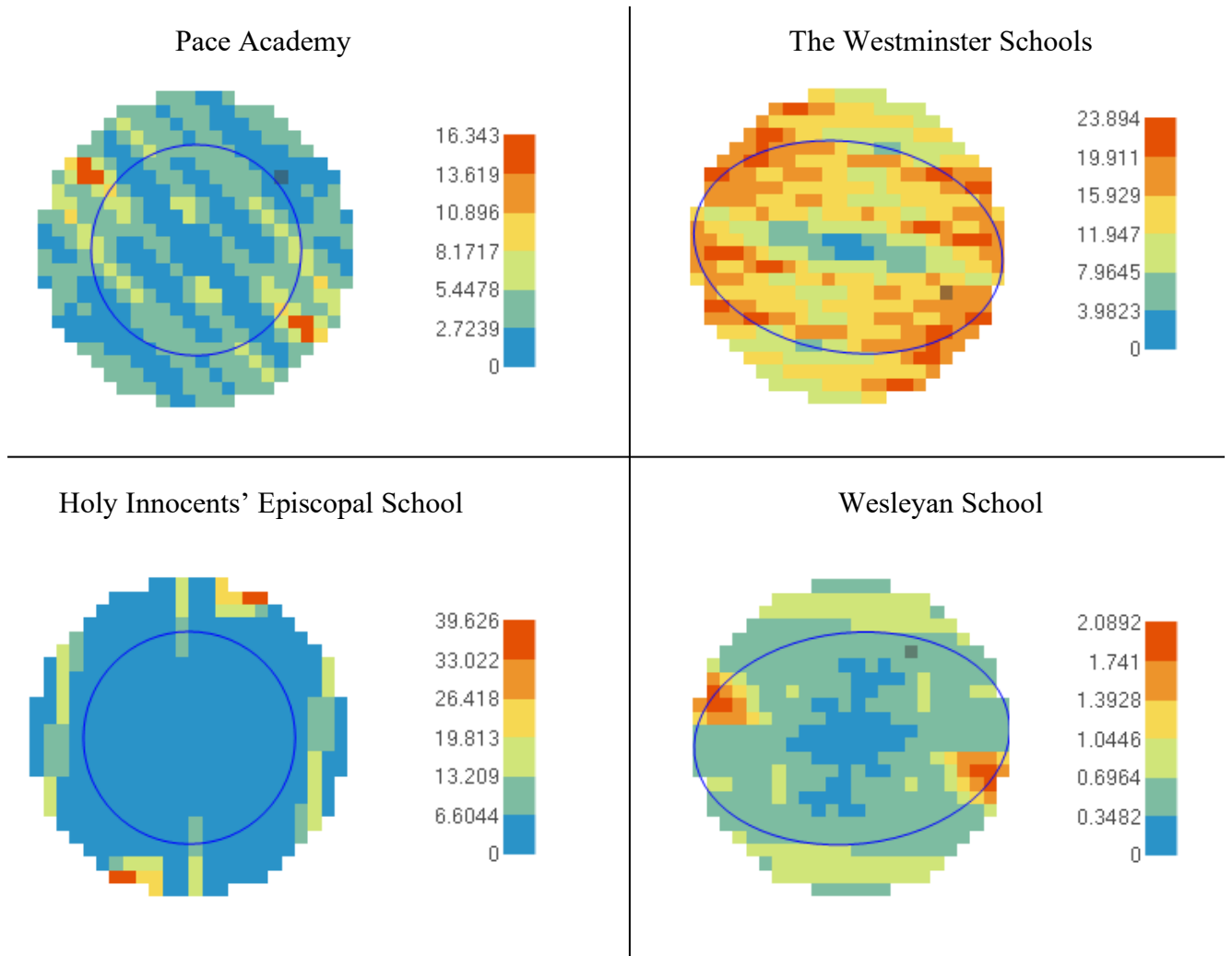


Figure A.1. Semivariogram maps from ordinary kriging of ECa data