SPATIOTEMPORAL VARIATION OF TURFGRASS SPORTS FIELDS AND ITS INFLUENCE ON ATHLETES' PERCEPTIONS AND INJURY OCCURRENCE

by

CHASE M. STRAW

(Under the Direction of Gerald M. Henry)

ABSTRACT

Within-field variations of natural turfgrass sports field properties occur due to foot traffic, field construction, management, and weather. Minimal studies have been conducted to better understand the influence of within-field variations on athletes' perceptions and injury occurrence. Precision Turfgrass Management is a new concept that involves the application of management inputs only where, when, and in the amount needed to potentially mitigate within-field variability while fostering a more sustainable management approach. Currently, its application on sports fields has received little attention. Therefore, four studies were conducted using a wide array of quantitative and qualitative methods to 1) increase the understanding of the impact of within-field variability on athletes' perceptions and ground-derived injury occurrence and 2) further the concept of Precision Turfgrass Management on sports fields. The first study found that athletes perceived within-field variations of turfgrass coverage and surface evenness to be most important. They expressed awareness of potential influences that variations could have, but not all made behavior changes. Those who reported changing did so with regard to athletic maneuvers and/or strategy, primarily for safety or context of play. The next study determined that an increased ground-derived injury occurrence happened in areas of significantly low turfgrass quality ($P < 0.001$) and high soil moisture ($P < 0.05$). Interestingly, most injuries occurring in significantly high or low areas of turfgrass quality, soil moisture, and surface hardness were along edges of high and low areas within the fields. The third study observed several significant relationships between measured properties, although significance did not always result in comparable spatial distributions and relationships were not always similar between fields of different soil textures. Lastly, the fourth study determined that soil moisture at the time of sampling can strongly influence site-specific management unit delineation and considerations should be made prior to sampling based on the objective. It is concluded that future studies evaluating athletes' perceptions and injury occurrence on natural turfgrass sports fields should account for within-field variability. Key surface properties and suggested sampling strategies from each study may be useful for the progression and implementation of Precision Turfgrass Management on turfgrass sports fields.

INDEX WORDS: athlete injury, athlete perceptions, GIS, hot spot analysis, kriging, NDVI, surface hardness, turfgrass shear strength, volumetric water content

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CHASE M. STRAW

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by

CHASE M. STRAW

Major Professor: Gerald M. Henry

Committee: Robert N. Carrow
Jennifer J. Thompson
Cathleen N. Brown Crowell
Gerald Shannon

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iv

CHAPTER

1 **LITERATURE REVIEW** 1

2 **ATHLETES' PERCEPTIONS OF WITHIN-FIELD VARIABILITY ON NATURAL TURFGRASS SPORTS FIELDS** 39

3 **DOES VARIABILITY WITHIN NATURAL TURFGRASS SPORTS FIELDS INFLUENCE GROUND-DERIVED INJURIES?** 73

4 **SPATIOTEMPORAL RELATIONSHIP OF PLANT AND SOIL PROPERTIES IN NATURAL TURFGRASS SPORTS FIELDS** 101

5 **SPATIOTEMPORAL VARIATION OF SITE-SPECIFIC MANAGEMENT UNITS ON NATURAL TURFGRASS SPORTS FIELDS DURING DRY DOWN** 133

6 **CONCLUSIONS** 176

Chapter 1

LITERATURE REVIEW

Playing surfaces are essential for athletic competition. Sports played on an athletic field typically have either natural turfgrass or artificial turf surfaces. Much focus with regards to athlete biomechanics and injury risk has been given to the comparison of the two surfaces (Meyers and Barnhill, 2004; Andersson et al., 2008; Dragoo and Braun, 2010; Meyers, 2010; Williams et al., 2011; Galbusera et al., 2013; Kent et al., 2015); however, each surface has received minimal attention alone. Natural turfgrass sports fields are highly variable depending on several factors, such as turfgrass species, soil texture, drainage capabilities, usage, and management (Miller, 2004; Stiles et al., 2009; Carrow et al., 2010; James, 2011; Orchard et al., 2013; Straw et al., 2016; Straw and Henry 2017). Many studies have failed to account for such variations, particularly those comparing natural turfgrass versus artificial turf and large-scale epidemiology studies that include a high number fields (Orchard, 2001; Orchard et al., 2005; Ramirez et al., 2006; Gabbett et al., 2007; Takemura et al., 2007; Twomey et al., 2012a, b). Using the term “natural turfgrass” without providing sufficient descriptions of the field can obscure results by masking between- and within-field variations. This makes it difficult to identify specific field characteristics that increase athlete injury occurrence (Stiles et al., 2009; Rennie et al., 2016).

The purpose of this review is to highlight the between- and within-field variations of natural turfgrass sports fields and their implications on athlete-surface interactions. In doing so, we discuss the various ways natural turfgrass sports field properties have been objectively quantified in the field. We review current literature involving athlete-surface interactions on natural turfgrass sports fields, from an athlete biomechanical and injury standpoint, and then discuss its limitations. We conclude by suggesting several needs to assist future studies evaluating athlete-surface interactions on natural turfgrass sports fields.

Natural turfgrass sports fields

Natural turfgrass sports fields have two primary components: turfgrass and soil. The most common turfgrasses for sports fields are bermudagrass (*Cynodon* spp.), Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass (*Lolium perenne* L.), but seashore paspalum (*Paspalum vaginatum* L.) and tall fescue (*Festuca arundinacea* Schreb.) are also used in certain scenarios (e.g. on professional-level baseball fields and recreational-level fields, respectively) (Puhalla et al., 1999). Each provides certain qualities, such as strong intermediate rhizomes (bermudagrass, Kentucky bluegrass, seashore paspalum), robust vegetative growth (all except seashore paspalum), and moderate to excellent wear resistance (all except seashore paspalum) that produce successful sports fields (Puhalla et al., 1999). All of these turfgrasses can be maintained at a desirable height for play; however, mowing heights may vary (1.9-5.1 cm) depending on turfgrass species, climate, season, sport, and competition level (Puhalla et al., 1999).

Climate is the primary dependent for selecting which turfgrass species to use for a sports field (Turgeon, 2011). Bermudagrass and seashore paspalum are warm-season turfgrasses that are typically found on sports fields in warmer climates, whereas Kentucky bluegrass, perennial ryegrass, and tall fescue are cool-season turfgrasses and typically found on sports fields in cooler climates (although tall fescue does not perform well in extreme cold) (Christians et al., 2016). It is not uncommon to overseed bermudagrass with perennial ryegrass in climates where bermudagrass goes dormant in the winter months, nor is it uncommon to have mixtures of cool-season turfgrasses (Turgeon, 2011). Within each warm- and cool-season turfgrass species, further selection is then based on the scenario of its intended use and the potential for success. For example, Kentucky bluegrass is slow to establish from seed and sod may be costly; therefore, tall fescue may be a better option on a recreational-level field that receives excessive use, since it can establish quicker and re-seeding would not be as expensive as Kentucky bluegrass sod (Puhalla et al., 1999).

Soils used for natural turfgrass sports fields can vary (James, 2011). The soil provides a medium for turfgrass growth, but its texture (i.e. proportion of sand, silt, and clay) effects soil chemical (e.g. cation exchange capacity, pH) properties, field management, and overall field safety and playability (Puhalla et al., 1999). Fine textured soils (i.e. clay) have a higher water holding capacity, are more susceptible to soil compaction, and typically higher strength (i.e. greater resistance for displacement) than course textured soils (i.e. sand) (Beard, 1973; Carrow and Petrovic, 1992; James, 2011). This is due to the compatibility of smaller clay particles (< 0.002 mm) compared to larger sand particles (2-0.05 mm), which results in more compacted soil with less macropores and more micropores that restricts air and water movement (Carrow and Petrovic, 1992). Sports fields with high clay content usually require less water and fertility, but may be susceptible to harder surfaces under low soil moisture conditions or puddling due to poor water infiltration after rainfall (Guisasola et al., 2010a, b; James, 2011). Conversely, sand sports fields generally require more water and fertility, but are less prone to soil compaction or standing water at the surface after rainfall (Guisasola et al., 2010a, b; James, 2011). Since sand sports fields have less divot resistance (i.e. complete removal of the turfgrass plant from the root zone), synthetic reinforcement materials have been incorporated into the root zone to increase divot resistance after roots are reduced from foot traffic (Baker, 1997; McNitt and Landschoot, 2003, 2005; Serensits et al., 2011; James, 2011). All soil scenarios may have a significant impact on the turfgrass system if improperly managed (Puhalla et al. 1999).

Turfgrass and soil combinations can also differ significantly. The soil texture of sports fields constructed on native soil will change between regions (Beard, 1973). Some facilities will construct their sports fields on man-made soil mixtures, such as the United States Golf Association specification, which typically has ~30 cm of sand over a ~5.1-10.2 cm layer of very coarse sand and fine gravel and a ~10.2 cm layer of pea gravel with drainage pipes beneath (Puhalla et al., 1999). Native soil fields are generally recreational-level fields, whereas fields constructed on man-made soil mixtures are more common at higher-end community level, collegiate, semi-professional, and professional level fields (James, 2011). The species of turfgrass is much less variable and primarily selected based on climate (as previously mentioned) (Puhalla et al., 1999); however, cultivars within species may be different and selected based on specific traits that are advantageous (e.g. shade tolerance, disease resistance) for a particular field scenario (Bonos et al., 2006; Baldwin and McCarty, 2007).

Furthermore, the overall quality of a field will range by sport, competition level, usage, budget, drainage capabilities, and management (Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway and Baker, 1993; Baker and Woollacott, 2005; James, 2011). Sports that involve athletes digging into the surface and pushing (such as American football or rugby) may be more detrimental to the turfgrass than sports where athletes are primarily running (such as soccer, aside from goal mouth areas) (Carrow and Petrovic, 1992). Fields designated for lower levels of competition (e.g. youth, intramural, club) typically have smaller sized athletes that cause less negative impact on the turfgrass and soil; however, these fields may receive excessive turfgrass wear and soil compaction due to native soil construction and increased usage (Adams and Gibbs, 1994). Conversely, fields designated for higher levels of competition (e.g. collegiate, professional) typically have larger sized athletes that cause more negative impact to the turfgrass and soil, but these fields are often better constructed, receive less usage, and have an increased management budget to maintain a higher standard of quality than lower levels of competition (Adams and Gibbs, 1994; James, 2011).

Natural turfgrass sports field performance testing

Objective measurements of surface properties in the field

Considerable studies have used subjective classifications (e.g. “good”, “satisfactory”, or “poor”) to assess natural turfgrass sports fields (Andresen et al., 1989; Hagel et al., 2003; Meyers and Barnhill, 2004; Ramirez et al., 2006; Gabbett et al., 2007; Meyers, 2010). Although convenient, this method is not reliable because the majority of these studies do not report specific definitions describing their subjective classifications (e.g. what is “good”?) and the measurements cannot be replicated (Petrass and Twomey, 2013; Rennie et al., 2016). “Performance testing” is a term used in the sports turf industry and refers to in-situ (i.e. in the field) quantification of field characteristics using objective measures (McAuliffe, 2008; Bartlett et al., 2009; Carrow et al., 2010; Straw and Henry, 2017). Several sampling devices, sampling strategies, and data analyses have been utilized to objectively describe natural turfgrass sports fields, but only the most common will be discussed in this section.

Surface hardness (or “ground hardness”) is the most frequently quantified field characteristic on natural turfgrass sports fields (Bell and Holmes, 1988; Baker and Gibbs, 1989; Baker, 1991; Miller, 2004; Freeland et al., 2008; Caple et al., 2012a). The term “hardness” indicates the firmness of the playing surface, which includes stiffness (i.e. the ratio of force applied and its deflection) and resilience (i.e. the ratio of energy returned to an athlete after contact and energy applied before contact) (Baker and Canaway, 1993; Canaway, 1985; Aldahir and McElroy, 2014). The Clegg hammer is widely used to measure surface hardness on sports fields throughout the literature (Clegg, 1976). It has a missile of a known mass (typically 0.5 or 2.25 kg) with an accelerometer on the end that is dropped through a guide tube from a standard height (typically 45 cm) [American Society for Testing and Material (ASTM), 2010a]. Peak deceleration on impact relative to gravity is reported as Gmax (McNitt and Landschoot, 2003). The number of missile drops at a given location has varied. One drop is suggested by the ASTM (ASTM, 2010a), but in Australian football 3 drops is most common, because it correlates with athletes' perceptions (Aldous et al. 2005; Chivers et al. 2003). Twomey et al. (2014) demonstrated that there was a significant difference between 1 drop and 2, 3, or 4 drops ($P < 0.05$); therefore, the decision about the number of drops should be carefully considered when assessing surface hardness with a Clegg hammer.

Other researchers have used a penetrometer to measure surface hardness on natural turfgrass sports fields (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007; Straw et al., 2016). Although the penetrometer and Clegg hammer are not measuring the same thing (soil strength by depth of penetration and deceleration on impact at the surface, respectively), they are positively correlated (Holmes and Bell, 1986; Petrass and Twomey, 2013; Caple et al., 2012a). There are several types of penetrometers, most of which are handheld and have a cylindrical cone at the end of a shaft. Penetration into the soil surface is done by dropping a weight from a standard height onto the shaft (to measure the depth of soil penetration) or pushing manually (with a load cell incorporated to measure force of penetration to a certain soil depth) (Holmes and Bell, 1986; Caple et al., 2012a; Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007; Straw et al., 2016). Penetration resistance is an alternative term (to surface hardness) that has been used to describe penetrometer data (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017).

Traction indicates frictional forces applied to a playing surface, which are typically linear, horizontal, vertical, or rotational (Bell et al., 1985; McNitt et al., 1997; Baker, 1999; Aldahir and McElroy, 2014). Adequate traction is necessary for players to safely make athletic maneuvers, such as running and turning, without slipping, falling, or having their foot "trapped" in the turfgrass (Orchard et al., 2005). One of the first traction measuring devices involved a studded disc (Canaway and Bell, 1986). The engineered apparatus had a two handle torque wrench and used a 40 kg mass weight dropped onto the studded disc. The wrench is turned and measures the amount of rotational force needed to cause the turfgrass to fail (Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway et al., 1990; Baker, 1991; Bartlett et al., 2009). Shear vane devices are also available to provide an indication of rotational traction (Rogers et al., 1998; Stiles et al., 2011). These devices are similar to the studded disc apparatus; however, they have a shear vane foot that is inserted manually into the surface (as opposed to a weight being dropped) and a torque wrench handle measures the amount of force until the turfgrass begins to tear (Rogers et al., 1998; Stiles et al., 2011). Other instruments quantify shear in relation to divot removal by measuring the force required to pull a shaft through the turfgrass surface in an arching motion (i.e. linear traction) (Caple et al., 2012a, b).

It should be noted that Twomey et al. (2011) conducted a study investigating the inter- and intra-rater reliability between experienced and novice users of the Clegg hammer, penetrometer, and studded boot apparatus. They found that the inter- and intra-rater reliabilities were greater for the experienced testers than the novice testers with the Clegg and penetrometer, but the novice testers produced greater inter-rater reliability for the studded boot apparatus

(Twomey et al., 2011). These results suggest that potential variability can exist between testers with these devices, which could have strong implications in research where multiple testers are obtaining measurements.

A penetrometer equipped on the Toro Precision Sense 6000 (PS6000; a mobile data acquisition unit) has recently been introduced in sports field research (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017). One advantage of mobile devices over handheld devices is the consistency in which a measurement is obtained (e.g. consistent rate of the cone penetrometer entering the soil), as opposed to the various user errors that could occur with handheld devices (Straw et al., 2016). Mobile surface hardness devices (i.e. mobile Clegg) do currently exist, but have yet to be documented in published sports field research (personal communication with developing company). To the authors' knowledge, no mobile traction apparatus has been engineered that can be driven over a playing surface for rapid measurements. The Pennfoot (McNitt et al., 1997; McNitt et al., 2003), Tennessee Athletic Field Tester (Thoms et al., 2013), and BioCORE Elite Athlete Shoe-Surface Tester (Kent et al., 2012) are all examples of shoe-surface interaction measuring devices that can quantify various forces (e.g. linear and rotational traction, vertical impact) using hydraulic pressure. These devices are on wheels and can be manually pushed from one sample location to the next within a field. Potential user error is removed because forces are not applied by hand.

Soil moisture is the relative amount of water in a soil (Turgeon, 2011). The most common method to quantify soil moisture in turfgrass is with time domain reflectometry (TDR) or capacitance sensors (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017). Both measure changes in the soil dielectric constant (ε) as water fluctuates and report soil moisture as percent volumetric water content (Leib et al., 2003) Time domain reflectometry sensors transmit and reflect a high frequency voltage pulse along two metal probes once inserted into the soil. The permittivity and the velocity of the pulse are closely related to soil water content, since water has a much higher ε than air (ε = 80 for water and 1 for air) (Plauborg et al., 2005). Capacitance sensors measure the charge time of a capacitor to determine ε (using the given soil as a dielectric) (Dean et al., 1987). Handheld soil moisture devices are most prevalent in turfgrass, but the mobile PS6000 is also equipped with a capacitance sensor for rapidly measuring soil moisture (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017).

Turfgrass quality (i.e. color, coverage, density) has been primarily rated visually in turfgrass research (Morris and Shearman, 1998; Trenholm et al., 1999; McNitt and Landschoot, 2003). Haggar et al. (1983) introduced a spectral reflectance technique to quantify and differentiate green canopies from soil. This method has been utilized in several sports turf studies, especially in the United Kingdom with the Sports Turf Research Institute (Bell and Holmes, 1988; Baker and Gibbs, 1989; McClements and Baker, 1994). The sensor measures the reflectance of red (R) and near-infrared (IR) spectra to determine a radiance ratio [(R + IR)/ IR], where the greener the canopy the higher the ratio (Haggar et al., 1983). Normalized difference vegetation index uses a different ratio of red (R) and near-infrared (NIR) reflectance to calculate a vegetation index [(R-NIR)/(R+NIR), where higher ratios indicate more dense green color]. Handheld NDVI sensors have become most abundant in turfgrass research over the past two decades to quantify turfgrass quality and density (Trenholm et al., 1999; Bell et al., 2002, 2008; Bremer et al., 2011); however, their use in-situ on sports fields has been minimal. The mobile PS6000 device is equipped with NDVI sensors and has been recently used on sports fields (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017). Additionally, the use of NDVI on commercial drones (unmanned aerial vehicles) is becoming popular in agriculture (Xiang and

Tian, 2011; Primicerio et al., 2012), but has yet to be implemented in published literature regarding natural turfgrass sports fields.

Lastly, surface evenness has been quantified one of two ways. The first is with a straight edge to record localized changes in evenness (McClements and Baker, 1994; Bartlett et al., 2009). The second is with a profile gauge that has several independently moving rods in a frame that become displaced by surface undulations (Holmes and Bell, 1986; Holmes and Bell, 1988; Canaway et al., 1990; Baker, 1999).

Sampling strategies

The ASTM F1936 test procedure for measuring surface hardness on natural turfgrass sports fields is commonly used in the United States (ASTM, 2010b). It describes sampling locations for several sports. The test generally involves obtaining measurements from 10 locations in close proximity of specific areas such as end zones, goals, wings, and the center of the field (ASTM, 2010b). The Performance Quality Standards (PQS) are common sampling procedures for natural turfgrass sports fields in Europe [Bartlett et al., 2009; Institute of Groundsmanship (IOG), 2017]. They provide procedures to test several parameters (a total of 19), where the number of samples and tests locations vary by sport (Bartlett et al., 2009; IOG, 2017).

The majority of researchers have followed similar sampling strategies, but with slight variations. Typically, field data have been obtained from 3-15 locations in a field. The smaller sampling numbers within this range were generally chosen to reflect areas of high, medium, and low field usage (Holmes and Bell, 1986; Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway et al., 1990; Baker and Woollacott, 2005; Bartlett et al., 2009), while larger sampling numbers are associated with samples obtained on a grid across the field (Takemura et al., 2007;

Caple et al., 2012a). Other researchers, particularly in Australian football and cricket, have determined sample locations based on proximity of athlete positions, which were ≤ 20 locations in a field (Orchard, 2001; Twomey et al., 2012a, b). Most aforementioned sampling strategies involved taking 3-10 samples at each of the designated locations in a field.

Larger sampling strategies have been employed when the goal has been to create a spatial map of a particular surface property. Miller (2004) and Freeland et al. (2008) measured surface hardness from 80 (10.0 x 10.0 m sampling grid) and 77 (9.1 x 9.1 m sampling grid) locations within a field, respectively. Caple et al. (2012b) used a sampling grid (specific dimensions not reported) to obtain 135 or 150 samples of several properties on three fields. Straw et al. (2016) and Straw and Henry (2017) used the PS6000 and two sampling grid sizes [4.8 x 4.8 m (230-259 samples) and 4.8 x 9.6 m (120-130 samples)] and a 2.4 x 4.8 m sampling grid (~450-530 samples), respectively, to measure soil moisture, penetration resistance, and NDVI on multiple fields in each study.

Data analysis

To assess the results of a performance test the majority of studies have used descriptive statistics (Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway et al., 1990; Caple et al., 2012a). The 3-10 samples obtained from each sample location are generally averaged. Data are then typically averaged across a field for comparison with other fields (Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway et al., 1990; Caple et al., 2012a), or specific sample locations are pooled together from several fields to compare values between certain areas within the fields (e.g. goal areas versus center of the field) (Holmes and Bell, 1986; Canaway et al., 1990; McClements and Baker, 1994; Baker and Woollacott, 2005). Bar graphs have been used to show the spatial variation in magnitude with the pooled averages from specific sample locations

(Holmes and Bell, 1986). Line graphs or scatter plots have been used to show averages from several test procedures overtime on individual fields (Baker and Gibbs, 1989; Baker, 1991; Caple et al., 2012a). Correlation coefficients (Holmes and Bell, 1986; Bell and Holmes, 1988; McClements and Baker, 1994; Caple et al., 2012a), regression (Holmes and Bell, 1986; Bell and Holmes, 1988), or principal component analysis (Bartlett et al., 2009) from all data pooled together have also been used to evaluate relationships between measured properties.

There have been some studies utilizing spatial analysis to create maps of surface properties. Maps are generated in Geographic Information System software from georeferenced (i.e. using a GPS to obtain latitudinal and longitudinal coordinates) field data (Miller, 2004; Freeland et al., 2008; Caple et al., 2012b; Straw et al., 2016; Straw and Henry, 2017). Maps are of interest because they aid in identifying small-scale within-field variations; however, they require larger sample sizes than studies that analyze field data with descriptive statistics (Straw et al., 2017). Most natural turfgrass sports fields will exhibit within-field variations to some degree due to foot traffic from play, field construction, management, and weather (Caple et al. 2012; Straw and Henry 2017). Maps of sports field properties have currently been used to show spatial and temporal changes of within-field variations under various climatic and agronomic conditions (Miller, 2004; Freeland et al., 2008; Caple et al., 2012b; Straw et al., 2016; Straw and Henry, 2017).

Athlete-surface interactions with natural turfgrass sports fields

Athlete biomechanics

The majority of current research involving athlete biomechanics on natural turfgrass has compared natural turfgrass and artificial turf surfaces (Villwock et al., 2009; Drakos et al., 2010; Sassi et al., 2011; Galbusera et al., 2013; Kent et al., 2015). Our primary focus is on natural turfgrass variability; therefore, this section will highlight results from research involving athlete biomechanical implications between natural turfgrass scenarios (e.g. soil types). Studies evaluating the influence of shoe design and its biomechanical implications on natural turfgrass are also discussed, as well as studies conducted in the field *and* in a laboratory setting.

Guisasola et al. (2009) investigated the impact of two soil types (ryegrass grown on a sand and clay loam in portable trays) on human loading (9 male participants) during running in a laboratory experiment. Peak loading rate on the sand soil was significantly greater than on the clay loam soil ($P < 0.05$). This result was explained by a significantly higher dynamic stiffness on the sand soil compared to the clay loam soil ($P < 0.001$). The researchers also observed that dynamic stiffness of a soil was dependent on loading rate (i.e. as a soil is loaded more quickly it becomes more stiff) ($P < 0.001$) and that when the clay loam soil is dried its dynamic stiffness increases ($P < 0.001$) (Guisasola et al., 2009).

A laboratory study was conducted by Stiles et al. (2011) that compared human ground reaction force and kinematic data during running and turning (8 participants) to ryegrass grown on a clay, medium, or sandy soil. Surface hardness and shear strength were measured before and after participant testing with a Clegg hammer and cruciform shear vane, respectively, on each surface. A significantly higher peak loading rate was observed on the sandy soil (which was found to be the softest surface) compared to the clay ($P < 0.05$). No significant differences were observed with running kinematics between surfaces. The clay surface had significantly lower fifth metatarsal phalangeal impact velocities when turning (compared to the medium soil; $P < 0.05$) (Stiles et al., 2011).

The influence of footwear type (soccer boots with traditional studs, boots with molded studs, and boots designed for artificial turf) and soil density on loading within the shoe during running was evaluated under controlled conditions by Dixon et al. (2008). In-shoe pressure data (from 5 participants) were collected from “hard” and “soft” soil surfaces (1460 kg/m^3 and 1590 kg/m^3, respectively). No differences were observed in peak force or loading rate between the surfaces; however, heel pressure was significantly lower ($P < 0.05$) for the soft surface relative to the hard surface. No differences in peak force or pressure was found between footwear, but a lower rate of loading was revealed for the molded boot compared to the studded boot on the hard surface ($P < 0.05$) (Dixon et al., 2008).

Villwock et al. (2009) investigated the influence of rotational traction (measured with a mobile testing apparatus) in-situ on two natural turfgrass playing surfaces (Kentucky bluegrass with a small percentage of ryegrass grown on a native Michigan soil and a custom engineered soil consisting of 90% sand and 10% silt and clay) with 10 different cleats. The sand-based surface produced non-significant higher torques than the native soil and the rotational stiffness was similar between surfaces. Differences between cleats were noticeable between surface types, but statistical tests were not conducted to determine significant differences between the individual cleats (Villwock et al., 2009).

Other researchers have evaluated the impact of footwear on rotational stiffness, peak forces, and peak torques, but only under one natural turfgrass scenario. Smith et al. (2004) evaluated ground reaction forces when running on natural turfgrass in soccer boots versus soccer training shoes (6 participants). Turfgrass-covered force platforms were used in an actual sports field. It was found that soccer boots had greater forces and impact loading rates ($P < 0.01$) during running than the training shoes and that soccer boots reduced shock attenuation at impact. Differences in the forces occurring with the right and left foot at the ground were also observed ($P < 0.05$) (Smith et al., 2004). Galbusera et al. (2013) investigated soccer cleat design (metal and molded studs, as well as bladed) influence on rotational stiffness and peak sustainable torque (measured with a testing machine) on a perennial ryegrass and Kentucky bluegrass mixture grown in a sand and soil mixture in a laboratory. Highest peak torque was observed with the studded model cleats and the bladed cleats were comparable to other models (Galbusera et al., 2013). Kent et al. (2015) measured peak forces and torques relative to elite athletes (with the BioCORE Elite Athlete Shoe-Surface Tester) on an outdoor Kentucky bluegrass field under "dry" conditions. Nineteen different American football cleats were tested and peak forces and torques were found to vary by cleat (Kent et al., 2015).

Sleat et al. (2016) conducted a unique study where surface hardness (objectively measured in the field from 11 matches; number of fields not clear) was compared to one male soccer athlete's movement response and performance frequencies. Hardness measurements obtained from a field were averaged and grouped into two categories: "harder" and "softer". They found that high intensity shuffling frequency was significantly greater on softer surfaces than harder surfaces ($P < 0.05$). A large effect size was also recognized on softer surfaces with running, dribbling, and low, moderate, and high intensity activities, as well as sharp path changes to the right and v-cut path changes, compared to harder surfaces (Sleat et al., 2016).

Athlete injuries

Speculation about a potential relationship between surface hardness and athlete injury has been given significant attention in the literature (Orchard, 2001; Orchard et al., 2005; Stiles et al., 2009; Petrass and Twomey, 2013; Rennie et al., 2016). The hypothesis is derived due to the fact that harder surfaces generally have increased peak reaction forces when an athlete lands/falls or applies a force (Dixon et al., 2008; Stiles et al., 2011; Twomey et al., 2012a). Game speed may also increase with harder surfaces, which could also lead to injury due to higher collision rates, fatigue, or exposure to excessive or prolonged loading (Norton et al., 2001; Rennie et al., 2016). Increased shoe-surface friction (i.e. traction) has also been given significant attention (Orchard, 2001). This hypothesis results from the belief that too much traction may lead to twisting injuries of the knee and ankle, while too little traction may cause athletes to slip or fall (Nigg and Segesser, 1988; Lambson et al., 1996; Orchard et al., 2005; Drakos et al., 2010). Other surface characteristics that can be objectively measured, such as turfgrass quality, soil moisture, surface evenness, and soil texture have received minimal attention. Despite surface hardness and traction being considered the two most influential field properties regarding athlete injury (Orchard, 2002; Chivers, 2007; Stiles et al., 2009), only surface hardness has been objectively measured for comparison to injury occurrence.

Orchard (2001) conducted a penetrometer study in the Australian Football League (AFL). Ground hardness was measured at 20 locations (corresponding with athlete positions) on several fields before 571 matches over the period of 1997-2000 and ACL injuries were recorded. He observed a non-significant trend towards a higher risk of ACL injury on harder playing surfaces and on surfaces comprised of bermudagrass (as opposed to ryegrass) (Orchard, 2001). Later, Orchard et al. (2005) investigated the contribution of ground hardness (measured with a penetrometer), grass type, and weather variables on ACL injury in the AFL over 12 years (1992-2004). Ground hardness was again not significant, but high evaporation and low prior rainfall was associated with increased ACL injury. Higher injury rates occurred in bermudagrass compared to ryegrass, which was hypothesized due to higher thatch levels (a layer of living and dead organic matter between the soil surface and turfgrass leaves) of bermudagrass causing an athletes' football shoe to become "trapped" in the surface (Orchard et al. 2005; Puhalla et al., 1999). Orchard et al. (2005) suggested that ryegrass may offer protection against ACL injury and it could be responsible for an observed northern bias for ACL injuries in the Australian Football league.

Takemura et al. (2007) also used a penetrometer to measure ground hardness from 20 fields before matches in rugby union. They found a non-significant relationship between injury incidence (of any kind) and ground hardness, and determined no association between injury incidence and the combination of ground hardness, rainfall, and evapotranspiration on the day of a match or cumulative rainfall and evapotranspiration prior to a match (Takemura et al., 2007). An early-season injury bias was observed where injuries decreased 2%/week, which resulted in nearly twice as many injuries in the first half compared to the second half of the season. Interestingly, ground hardness decreased significantly throughout the season ($P < 0.001$) (Takemura et al., 2007).

Other studies (that mostly did not obtain objective field data) have reported an early-season injury bias in American football (Andresen et al., 1989; Orchard and Powell, 2003), Australian football (Orchard, 2001; Orchard et al., 2002), English football (Hawkins and Fuller, 1999; Ekstrand et al., 2013), rugby league (Gabbett et al., 2007), rugby union (Alsop et al., 2000), and soccer (Ekstrand and Nigg, 1989; Hawkins et al., 2001). The two primary factors for the early-season injury bias are hypothesized to be variations in weather and ground conditions and athlete fitness and conditioning from the beginning of a playing season to the end (Aldahir and McElroy, 2014; Rennie et al., 2016); however, these reasons have yet to be fully investigated. Additionally, a climate bias (warm versus cool) has recently been proposed in Australian Football League and European soccer (Orchard et al., 2013). Ankle sprains and ACL injuries were more likely to occur in warmer climate zones, whereas Achilles tendinopathy may be more likely to occur in cooler climate zones. It is hypothesized that differences in climate or playing surface factors (grass species and shoe-surface traction) may be the reason for these results (Orchard et al., 2013), but further research is necessary.

Two studies have used a Clegg hammer to measure ground hardness for comparison to injuries. The first study monitored injuries in community level Australian football and linked them with ground hardness data (Twomey et al., 2012a). Ground hardness was obtained from 20 fields (from nine locations within each field that corresponded with athlete positions). Data were placed into five categories: unacceptably high (<120 g), high/normal (90-120 g), preferred range (70-89 g), low/normal (30-69 g), and unacceptably low (<30 g). Only a small percentage of injuries occurred in the unacceptable high and low hardness categories (3.7% and 0.3%, respectively). Relative to the preferred hardness range, the highest risk injury was associated with low/normal [relative risk 1.31 (95%CI: 1.06-1.62)] and unacceptable high hardness [relative risk 1.82 (95%CI: 1.17-2.85)], with the more severe injuries occurring with low/normal hardness (Twomey et al., 2012a). In the second study (Twomey et al., 2012b), injuries were monitored during 434 matches over the 2007-2008 playing season in junior cricket and matched to the same ground hardness categories as Twomey et al. (2012b). Thirty eight test sessions of ground hardness took place on match eve over the season on 19 fields (from 13 locations within each field that corresponded with athlete positions). Unfortunately, only 1 injury (out of 38 reported) occurred on a field that had ground hardness objectively measured; therefore, no statistical test could be made.

Limitations of previous research

Research comparing objectively measured ground conditions to athlete injuries has been in-situ (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012a, b), while athlete-surface biomechanics research has primarily been laboratory-based (with <10 participants) (Dixon et al., 2008; Guisasola et al., 2009; Stiles et al., 2011; Galbusera et al., 2013). As a consequence, there has been minimal correlations made between laboratory findings and field research. Biomechanical testing is difficult in either setting due to variations between human subjects (Stiles et al., 2009; Rennie et al., 2016), but can become increasingly challenging when attempting to incorporate a variety of turfgrass scenarios (i.e. combinations of turfgrass species and soil textures, as well as varying surface hardness/soil compaction and soil moisture levels). Manipulating these scenarios in a laboratory setting complicates research due to the potential differences (e.g. ambient conditions, soil moisture, turfgrass density, athlete movement speeds) between the laboratory and actual field (Stiles et al., 2009; Rennie et al., 2016). The findings in laboratory studies do emphasize significant differences in athlete biomechanics between cleats/shoes, which stresses the importance of future athlete injury research to report such information.

Ground-related biomechanics and injury studies that are conducted in-situ often fail to describe specific field characteristics and management practices (Orchard, 2001; Smith et al., 2004; Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012a, b; Kent et al., 2015). The turfgrass species and soil texture are perhaps the simplest field characteristics to identify, but are often unreported (Stiles et al., 2009). Differences in combinations of these two primary field characteristics influences ground hardness, traction levels, and athlete biomechanics (Canaway and Baker, 1993; McNitt et al., 2003; Dixon et al., 2008; Guisasola et al., 2009; Stiles et al., 2011; Caple et al. 2012a).

Fields with similar turfgrass species and soil textures can differ based on management practices and drainage capabilities (Bell and Holmes, 1988; Baker and Gibbs, 1989; Canaway and Baker, 1993; Baker and Woollacott, 2005). Two important management techniques rarely mentioned are mowing height and irrigation. Mowing height within turfgrass species can influence ground hardness and traction levels (Rogers and Waddington, 1992; McNitt et al., 2003; Caple et al., 2011), and soil moisture strongly effects these properties as well (Bell and Holmes, 1988; Baker, 1991; Caple et al. 2012a). With respect to athlete biomechanics, changes in soil moisture can significantly influence athlete loading due to its (negative) relationship with ground hardness (Guisasola et al., 2009, b; Stiles et al., 2011). Rainfall, temperature, and/or evapotranspiration has been included in injury studies (Orchard et al., 2005; Takemura et al., 2007), but supplemental irrigation has not. If only rainfall amount is reported, the reader is left speculating soil moisture conditions during periods of no rainfall, which may be extremely low in non-irrigated situations or moderate when irrigation practices are implemented. Both irrigation situations could have a strong influence on other field properties.

Studies using objective measurements to quantify field properties in relation to athlete injury have been limited to ground hardness measured with a Clegg or penetrometer (Orchard, 2001; Orchard et al., 2005; Takemura et al. 2007; Twomey et al., 2012a, b). A significant relationship between ground hardness and athlete injury was not evident by the findings in any study. Furthermore, researchers examining whether there was a relationship between Clegg readings and ground reaction forces generated by a human during a drop landing test found no significant correlation, which questions the ability of data generated by the Clegg hammer to relate surface hardness to athlete safety (Saunders et al., 2011). These results suggest that other options of objectively measured ground conditions, such as turfgrass coverage, soil moisture, and traction, should be explored for comparison to athlete injury.

Incorporation of GPS-equipped sampling devices for spatial map creation of natural turfgrass sports field properties provide an opportunity to explore the influence of within-field spatial and temporal variability on injury occurrence. Within-field variability of field properties are inevitable, but have yet to be accounted for in previous athlete biomechanics and injury studies. Recent literature describes that considerable within-field variations of soil moisture, penetration resistance, ground hardness, NDVI, and shear resistance (i.e. rotational traction) can exist on fields of different turfgrass species and soil textures used for a number of sports at various competition levels (Miller, 2004; Freeland et al., 2008; Caple et al., 2012b; Straw et al., 2016; Straw and Henry, 2017). Assuming that natural turfgrass sports field properties are homogenous (spatially *and* temporally) within and across all fields is completely inaccurate.

Other limitations should be noted that make comparisons between injury studies difficult. First, only five studies have used objective measures of ground conditions for comparison to injury incidence (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012a, b); therefore, comparison of results from these studies to the abundance of studies that used subjective measurements cannot be made. Secondly, injury definitions and methods of reporting (e.g. retrospective versus as the injury occurs) have varied, thus obscuring comparison of results because certain injuries may be included in one study and not considered in another or the validity of reported injuries may be questionable (Petrass and Twomey, 2013). Next, differences in data collection methods (i.e. number of sample locations) and analysis can influence interpretation of field property data potentially impacting results once comparisons to injury occurrence are made (Straw et al., 2017). Lastly, ample research has focused on professional level athletes that generally compete on fields of higher standard (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007), while minimal studies have attempted to connect ground conditions to lower levels of competition (Aldahir and McElroy, 2014).

Future needs

The influence of athlete biomechanics under a variety of turfgrass scenarios is not well understood. Our knowledge can be advanced with laboratory and in-situ studies. However, increased focus should be geared towards engineering and improving methodologies suitable for evaluating athlete biomechanics in the field, since these are the actual surfaces where athletes compete (Stiles et al., 2009). Progress is currently being made with the incorporation of pressure insoles in athletes' footwear and GPS-equipped athletic gear (with accelerometers) to measure loads at the foot plantar surface and monitor athlete movement patterns and intensity, respectively, during play (Ford et al., 2006; Tillman et al., 2012; Varley et al., 2012; Cummins et al., 2013).

It is essential that studies evaluating athlete-surface interactions with natural turfgrass sports fields report detailed field characteristics and management strategies, such as turfgrass species, soil texture, mowing height, and irrigation practices, in addition to athletes' footwear (Stiles et al., 2009; Petrass and Twomey, 2013). Several objectively measured field properties should be obtained and their impact on athlete biomechanics and injury occurrence evaluated. Current limitations are availability/cost of field data acquisition devices and sampling labor costs. Mobile, multi-sensor sampling devices (e.g. the PS6000) can be beneficial (Carrow et al., 2010; Straw et al., 2016; Straw and Henry, 2017), as would handheld devices that measure multiple field properties simultaneously (e.g. penetration resistance and shear resistance) (Caple et al., 2012a, b; Anderson et al., 2015). Unfortunately, these are currently not abundant, nor readily available. Improved field data acquisition devices are also needed that better represent and correlate to human biomechanics (Stiles et al., 2009; Saunders et al., 2011).

The recent incorporation of GPS technology into field data acquisitions entices an unexplored area of athlete-surface interaction research. That is, to determine the influence of within-field variations (utilizing spatial maps of field properties) on athletes' biomechanics and injury occurrence. While there is currently little understanding of this phenomenon, future studies should work towards developing consistent sampling and data analysis strategies. This holds true for studies without geo-referenced field data as well. One advantage of consistent sampling procedures and data analysis is the ability to compare findings between similar studies. For injury studies, adhering to generally accepted guidelines regarding injury classification and reporting is also important for study comparisons.

Lastly, future collaboration between disciplines (e.g. biomechanics and turfgrass science) is needed (Chivers, 2007). Intervention strategies and research trials should be conducted to identify surface properties (or combinations of surface properties) that lead to increased injury occurrence. The complexity of such studies would be extremely difficult for one discipline to attempt alone. Ultimately, the end goal is to develop evidence-based guidelines for sports field management that decrease injuries in a variety of turfgrass scenarios.

Conclusions

This review highlights the current challenge of assessing athlete-surface interactions on natural turfgrass sports fields due to their between- and within-field variability. Previous studies often fail to describe key surface characteristics, such as turfgrass species and soil texture. Although several field properties can be quantified, only ground hardness and traction have been strongly considered in-situ with respect to athlete biomechanical and injury research. Improved technology that assist with in-situ evaluation of athlete biomechanics and injury monitoring, coupled with spatial maps of several objectively measured field properties, could lead to a more robust and accurate assessment of athlete-surface interactions under a variety of turfgrass scenarios. There are currently many limitations, but a collaborative effort between disciplines should be attempted in order to begin moving towards the development and implementation of improved research strategies that construct and manage natural turfgrass sports fields in a manner that reduces injury occurrence.

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CHAPTER 2

ATHLETES' PERCEPTIONS OF WITHIN-FIELD VARIABILITY ON NATURAL TURFGRASS SPORTS FIELDS[1]

[1]Straw, C.M., G.M. Henry, J. Shannon, and J.J. Thompson. Submitted to *Precision Agriculture,* 09/25/2017.

Abstract

Natural turfgrass sports field properties exhibit within-field variations due to foot traffic from play, field construction, management, and weather. Little is known about the influences these variations may have on athletes' perceptions of field playability and injury risk. Information regarding athletes' perceptions of within-field variability could be fundamental for identifying key surface properties important to athletes, which may also be useful for the progression and implementation of Precision Turfgrass Management on sports fields. A case study using mixed methods was conducted on a recreational-level turfgrass sports field to better understand athletes' perceptions of within-field variability. Geo-referenced normalized difference vegetation index, surface hardness, and turfgrass shear strength data were obtained to create hot spot maps for identification of significant within-field variations. Walking interviews were conducted *in-situ* with 25 male and female collegiate Club Sports rugby and ultimate frisbee athletes to develop knowledge about athletes' perceptions of within-field variability. Field data, hot spot maps, and walking interview responses were triangulated to explore, compare, and validate findings. Athletes' perceptions of within-field variability generally corresponded with measured surface properties. Athletes perceived within-field variations of turfgrass coverage and surface evenness to be most important. They expressed awareness of potential influences the variations could have, but not all athletes made behavior changes. Those who reported changing did so with regard to athletic maneuvers and/or strategy, primarily for safety or context of play. Spatial maps of surface properties that athletes identified could be used for Precision Turfgrass Management to potentially improve perceptions by mitigating within-field variability.

Introduction

Natural turfgrass is a common playing surface for sports. Turfgrass managers aspire to produce high quality fields capable of sustaining competition (Canaway et al. 1990). Surface properties (e.g. turfgrass coverage, surface hardness, traction) can influence field playability (e.g. ball roll, ball bounce) (Bell and Holmes 1988; Canaway et al. 1990) and potentially increase injury risk (i.e. injuries caused or exacerbated by the playing surface) (Orchard et al. 2005; Twomey et al. 2012). Researchers have attempted to understand athletes' perceptions of surface characteristics to better understand their expectations and preferences. The majority of studies have been limited to evaluating perceptions of artificial turf fields (Zanetti 2009; Burillo et al. 2014), turfgrass versus artificial turf fields (Andersson et al. 2008; Poulos et al. 2014), or both types of fields combined (Ronkainen et al. 2012; Owen et al. 2017). No objective measurements of surface properties were obtained in these studies for comparison with athletes' perceptions.

A few studies have gathered athletes' perceptions of solely turfgrass sports fields, all of which compared questionnaire responses with objectively measured field data to develop playing standards in sporting leagues (Bell and Holmes 1988; Canaway et al. 1990; McClements and Baker 1994a, b; Aldous et al. 2005). These studies aimed at reaching a wide range of athletes across several fields and geographic locations. Although they provide a general understanding of athletes' perceptions about turfgrass sports fields, close-ended questionnaires limited the researcher's ability to understand athletes' detailed rationales for rating the fields (typically "good", "satisfactory", or "poor") and the consequences of athletes' perceptions on their behavior. Qualitative inquiry is gaining appreciation in sport and exercise research (Dale 1996), because it allows us to examine social phenomena in the real world by emphasizing the experiences and views of people (Pope and Mays 1995). Qualitative methods, such as interviews, can provide insight into athletes' perceptions of field characteristics that cannot be quantified through close-ended questionnaires.

Furthermore, previous studies restricted athletes' perceptions to three areas in a field (e.g. the center, goalmouths, and wings) and questionnaire responses and field data (obtained from 5 or 6 sample locations within a field) were pooled across all fields for analysis (Bell and Holmes 1988; Canaway et al. 1990; McClements and Baker 1994a, b; Aldous et al. 2005). Surface properties of turfgrass sports field's exhibit within-field variations due to foot traffic from play, field construction, management, and weather (Caple et al. 2012; Straw and Henry 2017); therefore, pooling data obscures variability of surface properties within individual fields. Sampling devices for measuring surface properties can now be equipped with GPS for spatial map creation to visualize within-field variability. Spatial maps may be utilized for implementation of Precision Turfgrass Management (i.e. applying management inputs, such as water, fertilizer, and cultivation only where, when, and in the amount needed) to potentially improve field uniformity, yet more intensive sampling than the aforementioned studies is necessary to identify small-scale within-field variations (Carrow et al. 2010; Straw and Henry 2017)

Combining interview responses with spatial maps may provide insight on athletes' perceived field playability and injury risk under various within-field conditions. Therefore, our objective was to conduct a case study using complementary qualitative and quantitative techniques to better understand 1) athletes' perceptions of within-field variability and 2) athletes' behavioral changes due to within-field variability. The goal is to identify key surface properties important to athletes, which may be useful for the progression and implementation of Precision Turfgrass Management on sports fields.

Materials and methods

Research site and participants

The study was conducted on a 'Tifway 419' hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) x *C. transvaalensis Burtt-Davy*] recreational-level sports field (67.1 m x 121.9 m) constructed on native soil (68% sand, 16% silt, and 16% clay) at the University of Georgia (Athens, GA). The field is the home field for Club Sports (men's and women's lacrosse, rugby, soccer, and ultimate frisbee), but also hosts non-sporting events (e.g. concerts, charitable races) and is open to the campus community and public for leisure. Club Sports are student-organized teams that compete against other schools and universities at the state, regional, and national level. For all Club Sports teams, games and practices are typically during the spring (January-May) and fall (August-December) academic semesters.

Participants (n = 25) were purposefully recruited from two Club Sports teams that practice and compete on the study field: rugby (13 athletes; seven male and six female) and ultimate frisbee (12 athletes; seven male and five female). We did not collect specific participant demographics; nonetheless, athletes were undergraduate freshman to graduate-level students at the university and several positions from each sport were represented (primary positions included three backs and ten forwards in rugby, and seven cutters and five handlers in ultimate frisbee). All participants were experienced playing on natural turfgrass sports fields. The University of Georgia Institutional Review Board approved the study prior to initiation. Athletes were instructed about study procedures and gave their informed consent to participate.

Data collection

Data collection consisted of two parts: 1) field testing to identify within-field variability of surface properties, and 2) walking interviews to understand athletes' perceptions and behavioral changes due to within-field variability. Field testing and walking interviews were conducted during the 2016 spring (April) and fall (October and November) academic semesters. Data collection was done at two time periods to evaluate if seasonal differences in field conditions influenced athlete responses.

Field testing

Normalized difference vegetation index (NDVI), surface hardness, and turfgrass shear strength were measured because they represent the primary surface properties believed to be related to field playability and injury risk (Canaway et al. 1990; Stiles et al. 2009; Aldahir and McElroy 2014; Rennie et al. 2016). We collected field data before and after athlete interviews in the spring (11 and 25 April) and fall (25 October and 3 November). All field data were obtained using a 4.6 m x 7.3 m sampling grid (~255 sample locations within the field). A NovAtel Smart-AG™ GPS (NovAtel Inc., Alberta, Canada) with sub-meter real-time accuracy was used to gather latitudinal and longitudinal information at each sample location within the field.

A GreenSeeker Model 500 active sensor (Trimble, Sunnyvale, CA) mounted to the rear of the Toro Precision Sense 6000 (a mobile sampling device; The Toro Company, Bloomington, MN) was used to obtain NDVI data. The sensor measured the reflectance of red (R = 660 nm ± 10 nm) and near-infrared (NIR = 770 nm ± 15 nm) spectra used to calculate the vegetation index {NDVI = [(R770 - R660)/(R770 + R660)]}. Red reflectance is affected by chlorophyll content (Knipling 1970), while near-infrared reflectance is influenced by leaf cell membrane and wall architecture (Gausman 1977), as well as leaf water status (Peñuelas et al. 1993). A healthy, dense turfgrass surface will have higher chlorophyll content (i.e. absorb more red light) and adequate leaf cell structure and water levels (i.e. reflect more near-infrared light) than a stressed, thinned turfgrass surface; therefore, NDVI provides an objective indication of visual quality and coverage (i.e. density) of turfgrass canopies (Trenholm et al. 1999; Bell et al. 2009; Bremer et al. 2011). Values are based on a 0-1 scale, where measurements closest to 1 indicate a healthy, dense turfgrass canopy.

A Clegg Impact Tester (Lafayette Instrument Co., Lafayette, IN) was used to measure surface hardness of the field (Clegg 1976). Surface hardness measurements represent the degree in which the ground absorbs energy created by an athlete (Orchard 2002). The Clegg had a 2.25 kg missile with an accelerometer at the end used to calculate Gmax (i.e. the ratio of peak deceleration on impact in gravities to the acceleration due to gravity) (McNitt and Landschoot 2003). The missile was dropped once from a height of 0.45 m through a guide tube at each sample location to obtain a measurement (ASTM F1702-10 2010). Higher Gmax values indicate a harder surface.

Turfgrass shear strength was measured with the Turf-Tec Shear Strength Tester (Turf-Tec Int., Tallahassee, FL). Data from this device is an indication of rotational traction when an athlete plants their foot and pivots on the surface. A shear vane foot at the end of the apparatus had twelve rectangular blades (six 19.1 mm length, 19.1 mm height, and 1.6 mm width and six 7.9 mm length, 19.1 mm height, and 1.6 mm width) fixed at 30° angles on a circular plate (7.0 cm diameter). The blades were inserted completely into the soil surface and a torque wrench handle was turned steadily (manufacturer recommendation). The highest amount of torque (Nm) required until the turfgrass began to tear was recorded by a follower needle on the wrenches gauge. Higher torque values indicate greater shear strength.

Walking interviews

Interviews (12 and 13 in spring and fall, respectively) were conducted *in-situ* and consisted of one interviewer walking the field and having a semi-structured discussion with each athlete about their perceptions and experiences of within-field variability. Walking interviews have become a valuable way to conduct geo-referenced 'on the move' interviews that "generate richer data, because interviewees are prompted by meanings and connections to the surrounding environment and are less likely to try and give the 'right' answer" (Evans and Jones 2011, p. 849). We developed an interview guide that contained several open-ended questions regarding the study field. For example, 'What would you consider the worst location on this field?' and 'What influence would this location have when playing?' Athletes were requested to take the interviewer to specific locations of interest within the field when necessary. Clarification and elaboration probes, such as 'What specifically about this location makes it the worst?' or 'Why would you do that differently here, as opposed to anywhere else on the field?' were used when athletes did not provide a clear answer to initial questions (Patton 1990). Athletes were not aware of the measured surface properties, nor were the properties discussed with the athletes by the interviewer. All interviews were audio recorded in their entirety to ensure accuracy of the responses. After the 25 interviews, it was apparent that we had reached data "saturation," where no new themes were being raised by athletes (Patton 1990; Guest et al. 2006; Hagaman and Wutich 2017).

Site-specific conversations within the field during walking interviews were geo-referenced using an alphanumeric grid generated with the "create fishnet" tool in ArcMap 10.3.1 (ESRI, Redlands, CA). The grid consisted of 3 m^2 cells that were each assigned a letter (A-V) and number (1-40) (880 total cells). The 3 m^2 cell size was chosen because it fit within the field's dimensions and was an adequate spatial scale large enough for the interviewer to correctly identify which cell conversations took place in while on the field and small enough to identify detailed spatial variations during analysis of field data. Once the grid system was made in

ArcMap, corresponding letter and number signs were hung in the field along an end line and sideline fence, respectively, to aid the interviewer in referencing what cell important conversations took place during the walking interviews. The interviewer made field notes to document specific grid cell locations and indicate the topic and time of conversations being discussed.

Analysis of field data

Normalized difference vegetation index, surface hardness, and turfgrass shear strength data from the two data collections each semester were averaged and used for further analysis. Descriptive statistics of surface properties (minimum, maximum, range, mean, standard deviation, and coefficient of variability) were computed in ArcMap to identify central tendencies and simple measures of variability (Appendix 2.1). Correlation coefficients were calculated using the ‘modified.ttest’ function in the SpatialPack package of RStudio 3.2.1 (Osorio and Vallejos 2014; RStudio Team 2015) to determine the strength and direction of relationship between all measured surface properties. The function accounts for the spatial association between the properties to calculate a corrected Pearson’s *r* correlation coefficient (Clifford et al. 1989; Dutilleul 1993).

Hot spot maps were created in ArcMap to identify significant within-field variations of NDVI, surface hardness, and turfgrass shear strength. To generate hot spot maps, the geo-referenced point data of each surface property were first interpolated using ordinary kriging (Fortin and Dale 2005). Kriged maps were saved as raster maps comprised of 1 m^2 pixels. The “zonal statistics as table” tool was used to find the average value of the pixels within each cell of the alphanumeric grid. The output was a spreadsheet with a value assigned to each cell on the field, which were added to the grid’s attribute table. Hot spot maps were then created using the “hot spot analysis” tool to calculate the G_i* statistic for each grid cell (Getis and Ord 1992). The result is a *z* score for each individual cell that can be used to assess significance. A positive and significant *z* score would indicate a “hot” spot (i.e. a red cell that has a higher value relative to all cells) and a negative and significant *z* score would indicate a “cold” spot (i.e. a blue cell with a lower value relative to all cells). Yellow cells are not significant and considered average values.

Analysis of interview data

Audio recordings of each walking interview were transcribed verbatim into Microsoft Word 2010 (Microsoft, Redmond, WA) by a single researcher and re-read several times to increase familiarity. Transcribed interviews were imported into the qualitative data analysis software ATLAS.ti 7.5.17 (Berlin: ATLAS.ti Scientific Software Development GmbH), which allowed for thematic analysis. Thematic analysis is “a method for identifying, analyzing, and reporting patterns (themes)” that are present in the qualitative data (Braun and Clarke 2006, p. 79). The objective of thematic analysis is to identify themes and organize key concepts in the data, rather than to quantify their prevalence (Braun and Clarke 2006). The analysis began with structural coding of the data based on the interview questions and mentioned field characteristics (e.g. an athlete’s response to the question about the “best” location on the field having high turfgrass cover might be coded “best location: turfgrass cover”), followed by pattern coding to group similar structural codes (e.g. grouping “best location: turfgrass cover” and “worst location: turfgrass cover” into “turfgrass cover”) (Saldaña 2015). Next, we identified and organized categories under each higher-order structural code (e.g. dust, surface hardness, and traction are categories of “turfgrass cover”). Where possible, we identified more specific sub-categories and topics that made up each category (e.g. falling/landing and running were topics under surface hardness) (Saldaña 2015). Hierarchy diagrams were constructed in Microsoft PowerPoint

(Microsoft, Redmond, WA) to illustrate the progression from the data (exemplar quotes from athletes) to the topics, categories, and ultimately the overarching themes. Themes identified from athlete responses were not different between semesters; therefore, quotes from both data collection periods are presented together in all of the hierarchy diagrams.

Steps were taken to minimize individual researcher bias and ensure quality of results. First, several open discussions throughout the entire interview process (from guide development to data analysis) were conducted between the interviewer and a senior research team member about clarity and structure of interview questions, coding strategy and meaning of codes, and progression of the hierarchy diagrams. The discussions involved negotiating clarity and validity of all decisions until consensus was reached (Sandelowski and Barroso 2003), and changes were made when necessary. Next, a colleague with experience in qualitative research was asked to validate our coding of emergent themes. She was given copies of transcribed interviews, as well as overarching themes and categories of the hierarchy diagrams. Her objective was to read the transcribed interviews to verify our emergent themes and to identify any major themes or categories that may have been overlooked. Upon completion, no additional themes or categories were identified.

Mixing methods

We anticipated that visual turfgrass quality and coverage, surface hardness, and traction at particular areas on the field would be mentioned during athlete interviews, which provided our rationale for quantifying similar surface properties. These are among the most commonly quantified surface properties, but we also anticipated that unexpected field characteristics could arise. To investigate our assumptions, and to enhance the exploratory power of our research (Pope and Mays 1995; Elwood 2010), we undertook a mixed methods analysis that included both quantitative (field data and hot spot maps) and qualitative (walking interview responses) data. As a result, this study is an example of qualitative GIS, an approach that combines qualitative and spatially referenced data to locate feelings, emotions, and perceptions in reference to geographic locations (Cope and Elwood 2009; Jung and Elwood 2010). We utilized qualitative GIS methodology by comparing interview responses from site-specific locations within the field to hot spot maps in order to evaluate if areas of interest to the athletes were locations of significantly high (i.e. hot spots) or low (i.e. cold spots) surface property values.

Results

Athletes' perceptions of within-field variability

Walking interviews began by asking each athlete to identify what they perceived to be the "best" and "worst" locations within the field. Athletes were asked to identify one area for each. When athletes identified areas that were larger than a single grid cell, the interviewer recorded the areas center most cell. That cell and its immediate neighbors were then considered. The location was deemed as a hot or cold spot if at least one cell within the area was significant. Perceived "best" locations were typically large areas (e.g. "the end zone behind the rugby post", cells A-V 35-40). A majority of athletes (76%) selected areas of significantly high NDVI and low surface hardness to be the best (Figure 2.1 and 2.2, respectively). Both significantly high and low turfgrass shear strength areas were selected by 52% of the athletes to be the best (Figure 2.3). Perceived "worst" locations were generally smaller areas. No athletes selected areas of significantly high NDVI, low surface hardness, or high turfgrass shear strength to be the worst (Figures 2.1-2.3). Most athletes (84%) selected areas of significantly low NDVI and low turfgrass shear strength to be the worst (Figure 2.1 and 2.3), while 56% selected areas of significantly high surface hardness to be the worst (Figure 2.2).

Two overarching themes emerged from athletes' perceptions and explanations of the "best" and "worst" locations within the field: turfgrass coverage and surface evenness (Figure 2.4 and 2.5, respectively). When athletes described a measured surface property at a specific location on the field, we report the corresponding grid cell(s) from the hot spot maps in the respective hierarchy diagram. These can be used to identify if quotes were made in or near a significant area of variability. Quotes that do not report grid cells were general statements made when athletes were discussing different areas on the field or recalling perceptions and experiences of within-field variability on other fields.

'Turfgrass coverage'

Turfgrass coverage was the primary explanation athletes used when identifying the "best" and "worst" areas within the field (Figure 2.4). This is supported by the percentage of athletes that took the interviewer to significantly high (76% for their perceived "best") and low (84% for their perceived "worst") NDVI locations (Figure 2.1). Athletes' perceptions associated with the turfgrass coverage theme were grouped into three categories: dust, surface hardness, and traction (Figure 2.4). Quotes focused on dust were generally negative and often perceived in bare areas. Surface hardness was made up of two sub-categories: falling/landing and running. Athletes perceived areas with high turfgrass coverage as softer surfaces to fall and land on when tackling and diving, respectively. Areas with high turfgrass coverage were also perceived as softer surfaces for running. Traction consisted of two sub-categories: cutting and scrumming. Cutting is an athletic maneuver where an athlete plants their feet into the ground and abruptly changes directions. Athletes perceived areas with high turfgrass coverage as better surfaces to make cuts due to the grip that is obtained from the turfgrass. Scrumming is a rugby term that involves the forward position players to push against one another to gain ball possession. Similar to cutting, athletes perceived that more grip for scrumming could be obtained from areas with higher turfgrass coverage.

Perceived relationships that athletes had between turfgrass coverage, surface hardness, and traction were verified by correlation coefficients calculated with measured surface property data. Relationships between NDVI and surface hardness were negative and significant both semesters [r = -0.68 ($P < 0.001$) and r = -0.58 ($P < 0.01$) in the spring and fall, respectively], which supports athletes' statements that higher turfgrass coverage results in softer ground. Relationships between NDVI and turfgrass shear strength were positive and significant both semesters [r = 0.64 ($P < 0.001$) and r = 0.26 ($P < 0.01$) in the spring and fall, respectively], which supports athletes' statements that higher turfgrass coverage results in higher traction.

'Surface evenness'

Surface evenness (i.e. consistency in the playing surface) was the second most common theme emerging in athletes' selection of "best" and "worst" areas within the field (Figure 2.5). Surface evenness was not a measured surface property, so quotes were not compared to hot spot maps. Although athletes did sometimes mention surface evenness in transition areas (i.e. areas going from bare ground to full turfgrass coverage), it was primarily discussed in areas where turfgrass was present but the surface also exhibited small undulations. The surface evenness theme consisted of two categories: ball bounce and body positioning (Figure 2.5). Perceptions regarding ball bounce were related to the difficulty of judging where the rugby ball was going to bounce once it hit uneven ground. Body positioning was made up of two sub-categories jumping/landing and running. Jumping and landing in uneven areas was a perceived concern to the athletes, because of the potential for knee and ankle injuries. Running contained three topics: convenience, fatigue, and stepping. Athletes perceived uneven ground to be inconvenient, since they had to pay attention to where they are running; they cited fatigue when running as an issue when playing in inclined areas on a field; and they voiced concerns about the potential for knee or ankle injuries when stepping on uneven ground (including holes).

Behavior changes due to within-field variability

Discussions about within-field variability continued by asking athletes how they actually change to compensate for differences within the field. We asked, "As you move from a 'good', to 'average', to 'bad' area within the field, or vice versa, do you knowingly change anything?" Two themes emerged from athlete responses: athletic maneuvers and strategy (Figure 2.6 and 2.7, respectively). Note the hierarchies contain the categories no change and change, because some athletes reported making changes with respect to both athletic maneuvers and strategy and others said they did not. We report the corresponding grid cell(s) from the hot spot maps in the respective hierarchy diagram when athletes discussed a specific location on the field.

'Athletic maneuvers'

Athletic maneuvers were considered any type of athletic movement during play (e.g. cutting, diving, running). Changes associated with the athletic maneuvers theme were grouped into two categories: no change and change (Figure 2.6). Some athletes acknowledged that although they recognize variations within the field, they make no changes in athletic maneuvers because they believe these areas are unavoidable. For athletes who described making changes to athletic maneuvers, their changes fell into two sub-categories: changes related to safety and those related to the context of play (Figure 2.6). Athletes who perceived within-field variability as a safety issue described two types of changes in their athletic maneuvers: avoidance and tentativeness. They described completely avoiding or proceeding tentatively in an area of field variability. Other athletes made changes in their athletic maneuvers based on the context of play.

They distinguished between practices and games, saying that they are more aware of within-field variability in practice and can make changes accordingly (e.g. avoid areas within the field), but in a game they do not have time think about it.

'Strategy'

A second theme that emerged in athletes' descriptions of the changes they make in response to field variability was strategy (i.e. plan of action) (Figure 2.7). Changes associated with the strategy theme were grouped into two categories: no change and change (Figure 2.7). Some athletes reported that they do not change strategy due to within-field variability because they perceive that the field is not a factor, or that they must adjust to the other team regardless of field conditions (Figure 2.7). The strategic changes athletes described fell into three sub-categories based on the context of play: practice, pre-game, and game (Figure 2.7). Changes in practice strategy due to within-field variability typically involved adjusting a practice drill according to the current field condition or completely moving to more appealing locations. Pre-game changes in strategy result from the athletes recognizing within-field variations before a game and either modifying their equipment or avoiding areas when warming up. Changes in game strategy caused by within-field variations involved where or how the rugby ball is moved throughout the field.

Discussion

We assumed within-field variations of visual turfgrass quality and coverage, surface hardness, and traction would be mentioned by athletes. Based on this assumption a close-ended questionnaire could have been developed regarding those surface properties. However, interviews encouraged athletes to describe their own perceptions of within-field variability, rather than assume that the field properties we measured were most important. Qualitative data analysis of interview responses allowed other surface characteristics to arise (e.g. dust and surface evenness) and assisted in developing an understanding of how athletes responded to within-field variations. Thus, the value of qualitative data cannot be understated when attempting to explain athletes' perceptions about playing surfaces. Although restricted to close-ended questionnaires and limited to three areas in a field, previous studies did determine that athletes have different perceptions about areas within a field (center and/or goalmouths had more "poor" responses, while wings had more "satisfactory" and "good" responses) and responses were strongly influenced by variations of turfgrass coverage (Bell and Holmes 1988; Canaway et al. 1990; McClements and Baker 1994a, b; Aldous et al. 2005). Similarly, turfgrass coverage, as well as surface evenness, strongly influenced athletes' perceptions in our study.

Interesting perceptions regarding injury risk should also be noted. Athletes that had been previously injured viewed within-field variability as a higher risk for injury. As a result, these athletes reported making changes to prevent another injury (or re-injury) more frequently than athletes who had not been previously injured. It was not our objective to compare the perceptions between athletes that had and had not been previously injured; but, it is worth mentioning some athletes referred to past injuries when describing their perceptions and changes, which suggests there may be a relationship that deserves more research. Moreover, many athletes reported they were more likely to change in practice due to perceived variations (versus changing in a game). Several researchers have reported that injuries occur substantially more often in games than practices (Hawkins and Fuller 1999; Ekstrand et al. 2004; Junge et al. 2004). Our results suggest that this could partially be attributed to athletes' willingness during games to perform certain athletic maneuvers within their perceived "worst" areas on a field, whereas they might avoid making these maneuvers, or avoid the "worst" area entirely, during practice.

Mixing methods proved to be a valuable methodology in evaluating athletes' perceptions of within-field variability. The term "triangulation" refers to the process of collecting data about same phenomenon through multiple methods, then comparing the findings to validate (or further interrogate) study conclusions (Jick 1979; Olsen 2004). Field data, hot spot maps, and walking interview responses were triangulated to validate one another, as well as further explore our findings. Walking interviews confirmed that the measured surface properties were of importance to athletes. Hot spot maps and walking interviews supported our expectation that athletes would identify and perceive areas of within-field variability corresponding to measured surface properties. Lastly, field data and walking interviews revealed athletes' perceived relationships between surface properties agreed with calculated correlation coefficients.

Study limitations

There are limitations worth mentioning. First, this was a case study where the participants were Club athletes from two sports and their perceptions were confined to one recreational-level field. Qualitative research generally has small sample sizes, because the objective is to develop a rich and nuanced understanding of the full range of people's experiences and perceptions rather than to quantify their prevalence (Sandelowski 1995; Cleary et al. 2014). Therefore, further investigation is needed about perceptions of within-field variability with athletes from different sports and experience levels, in addition to other types of fields. Similar locations of variability were often identified regardless of sport in this study, but perceptions about the consequences of these areas were sometimes different. No differences in perceptions between genders were identified; nonetheless, it should also be considered in future studies.

Next, changing perceptions based on the temporal variability of field conditions may have been overlooked. For example, athletes' perceptions could change in bare areas that are either dusty or muddy depending on soil moisture condition. Athletes mentioned both in this study, but dust was brought up more frequently probably due to relatively dry field conditions during the interview periods. Mud was mentioned much less frequently and typically only in the context of “if it rains.” Specific questions regarding such short-term temporal changes of within-field variability were not asked during our interviews, but they may be worth incorporating in future studies so that athletes’ perceptions about these changes are better understood.

Conclusions

A case study was conducted that compared hot spot maps of objectively measured surface properties with walking interview responses from athletes to evaluate their perceptions and behavioral changes regarding within-field variability of natural turfgrass sports fields. Athletes perceived within-field variations of turfgrass coverage and surface evenness to be most important. Although surface evenness was not measured, athletes’ perceptions about turfgrass coverage, as well as surface hardness and traction, generally corresponded with NDVI, surface hardness, and turfgrass shear strength hot spot maps. Athletes expressed awareness of several potential influences within-field variations could have (e.g. falling or slipping), but not all made behavioral changes. Athletes who reported making changes did so with regard to athletic maneuvers and/or strategy, primarily for safety or depending on context of play (e.g. practice, pre-game, or game).

Results from this case study exemplifies within-field variability of natural turfgrass sports fields can influence athletes’ perceptions and behavior. Perceptions of within-field variability were generally negative, so it should be the responsibility of all parties to work towards preserving and maintaining consistency within a field. For athletes, this may involve rotating practice drills or abiding requests to remain off the field during certain weather conditions. For turfgrass managers, this may involve Precision Turfgrass Management. Key surface properties identified were turfgrass coverage (a composite of dust, surface hardness, and traction) and surface evenness. Spatial maps of these surface properties generated from geo-referenced field data may aid in identifying or predicting areas of high use (although dust may be difficult to measure and maps of surface evenness have not yet been implemented on sports fields). Precision Turfgrass Management techniques, such as site-specific aerification, fertilization, or topdressing, to potentially mitigate or improve within-field variability could then be employed (Carrow et al. 2010; Straw and Henry 2017). This may lead to a safer, more playable, and accommodating sports field for athletes. Since Precision Turfgrass Management is currently an unimplemented theory, the effectiveness of suggested applications should be the next step for future studies.

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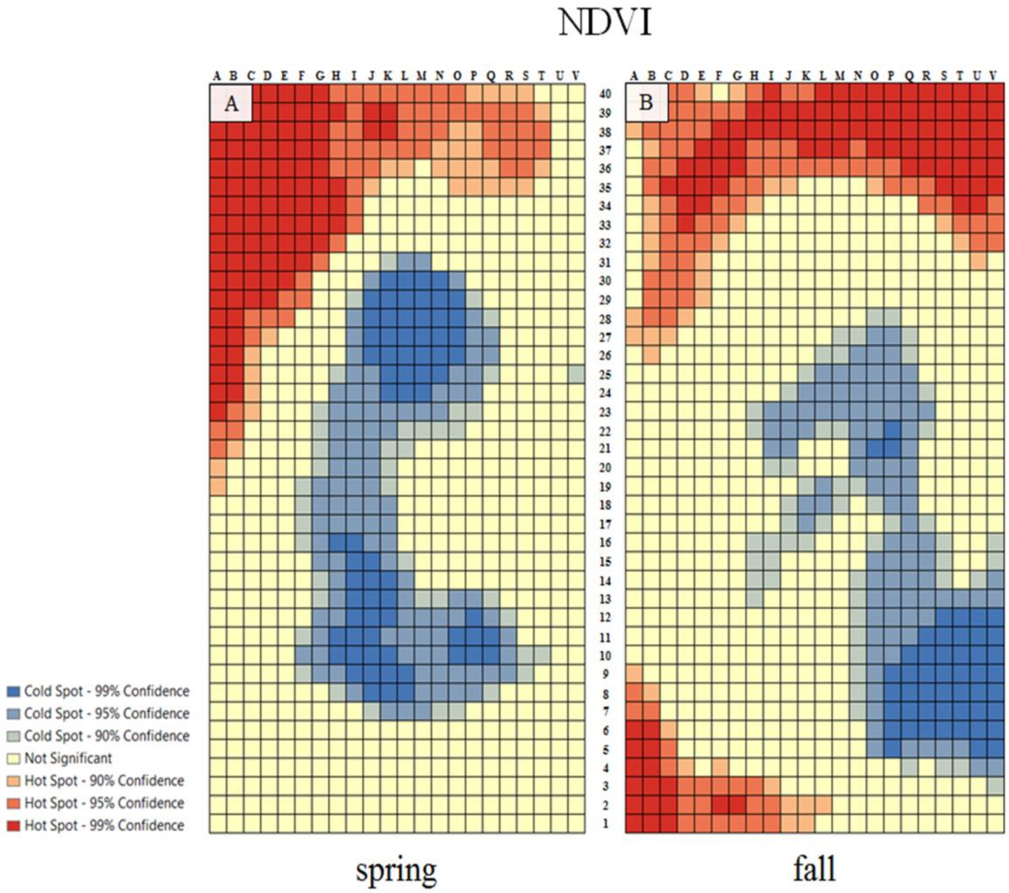

Figure 2.1 Hot spot map of normalized difference vegetation index (NDVI) from spring (left) and fall (right) academic semesters. A "hot" spot is a red cell that has a significantly higher value relative to all cells and a "cold" spot is a blue cell that has a significantly lower value relative to all cells. Yellow cells are not significant and considered average values.

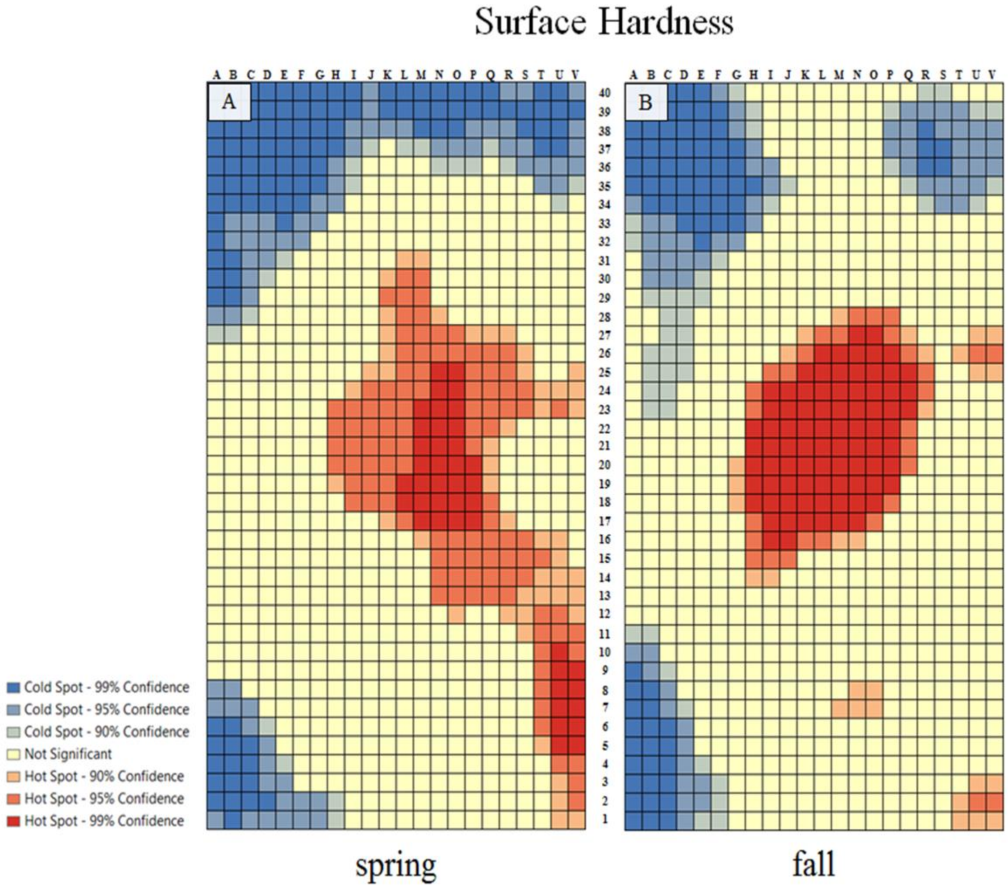

Figure 2.2 Hot spot map of surface hardness (Gmax) from spring (left) and fall (right) academic semesters. A "hot" spot is a red cell that has a significantly higher value relative to all cells and a "cold" spot is a blue cell that has a significantly lower value relative to all cells. Yellow cells are not significant and considered average values.

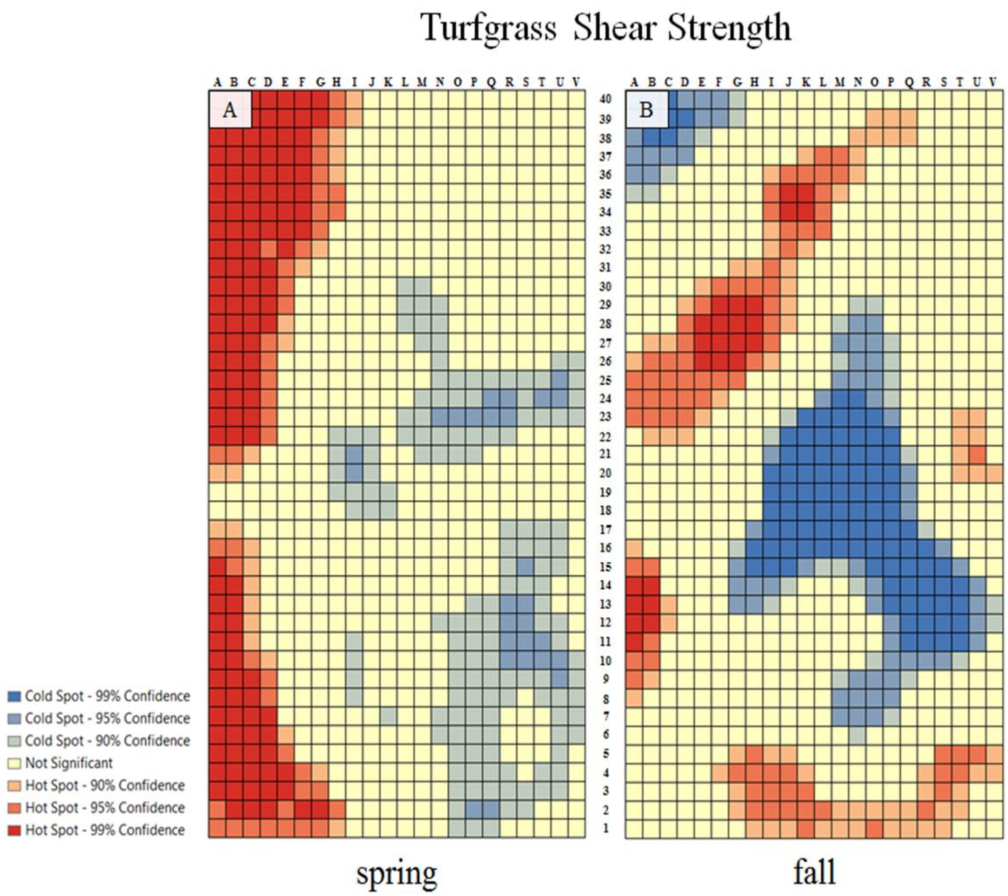

Figure 2.3 Hot spot map of turfgrass shear strength (rotational traction; Nm) from spring (left) and fall (right) academic semesters. A "hot" spot is a red cell that has a significantly higher value relative to all cells and a "cold" spot is a blue cell that has a significantly lower value relative to all cells. Yellow cells are not significant and considered average values.

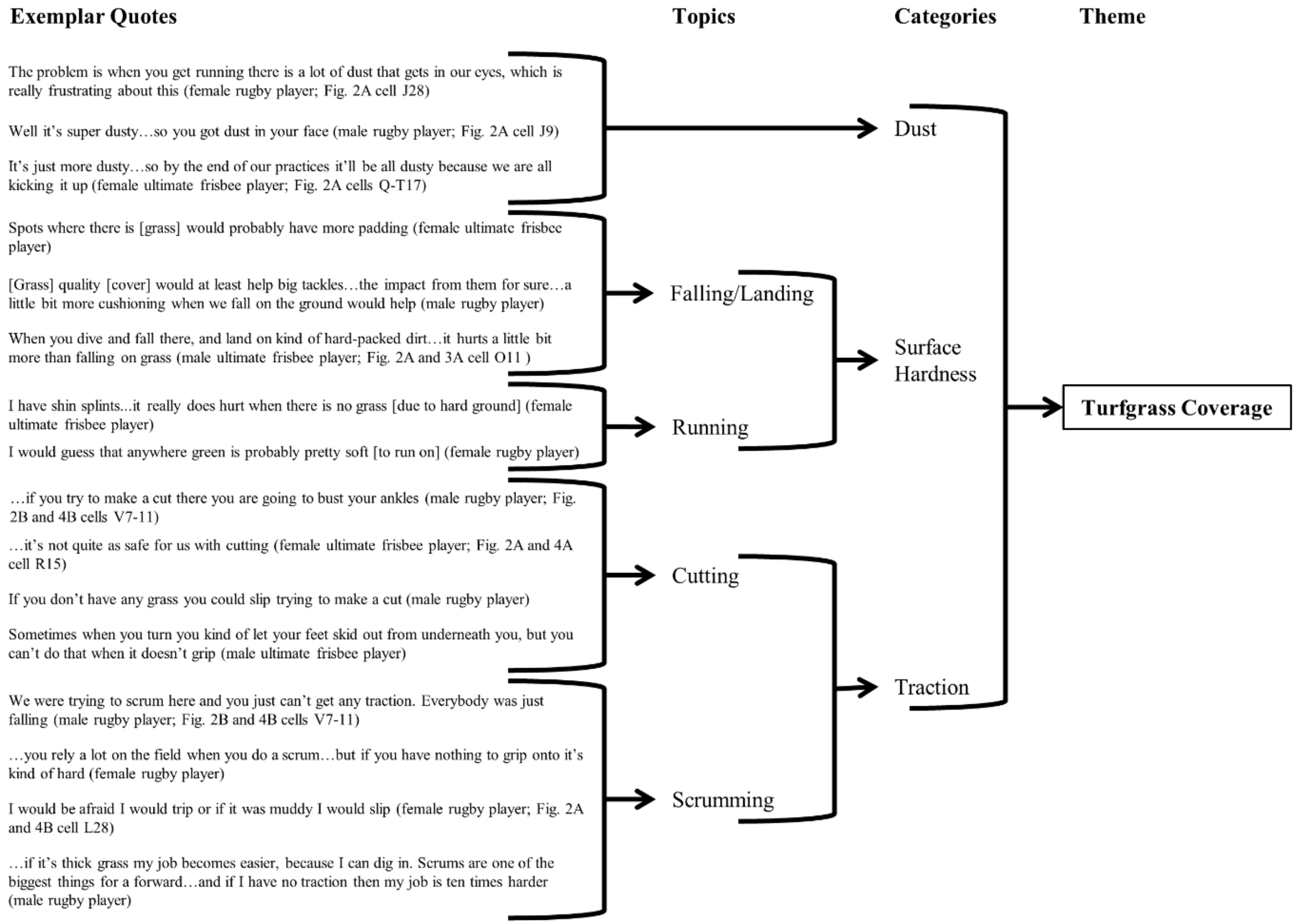

Figure 2.4 Hierarchy diagram of the theme 'turfgrass coverage'. Columns moving left to right illustrate the data (exemplar quotes from athletes), topics, categories, and ultimately the overarching theme.

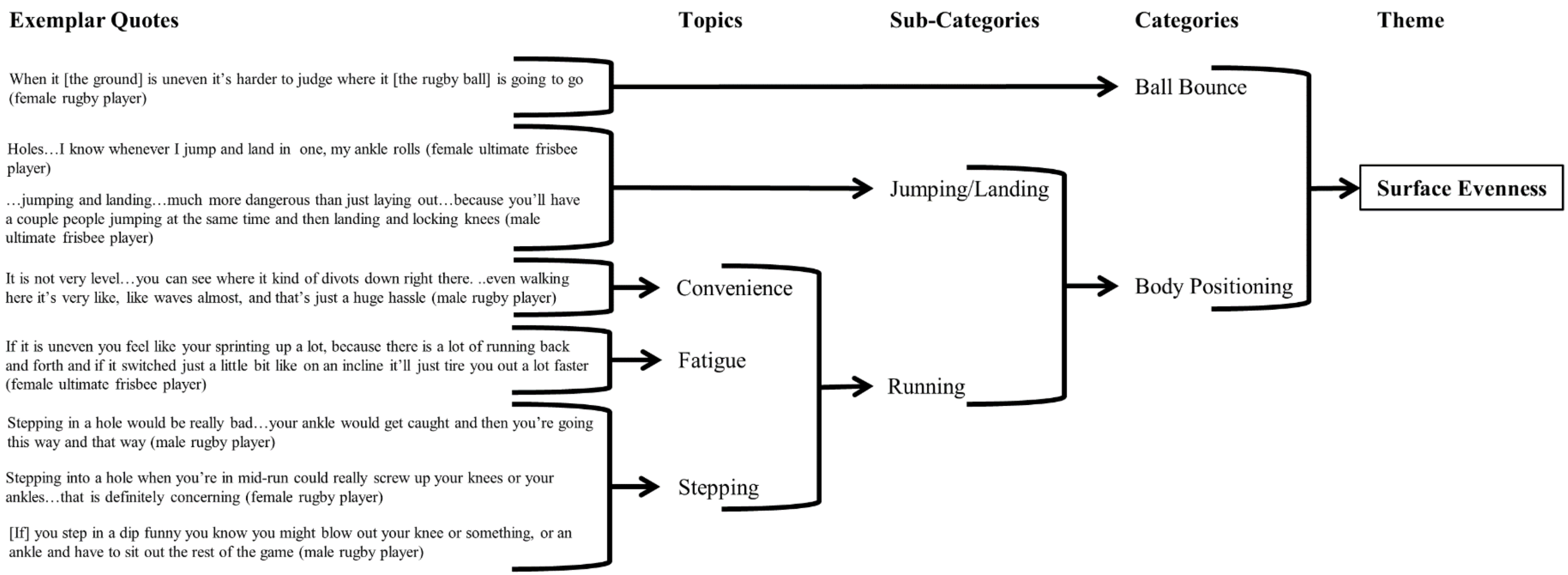

Figure 2.5 Hierarchy diagram of the theme 'surface evenness'. Columns moving left to right illustrate the data (exemplar quotes from athletes), topics, categories, and ultimately the overarching theme.

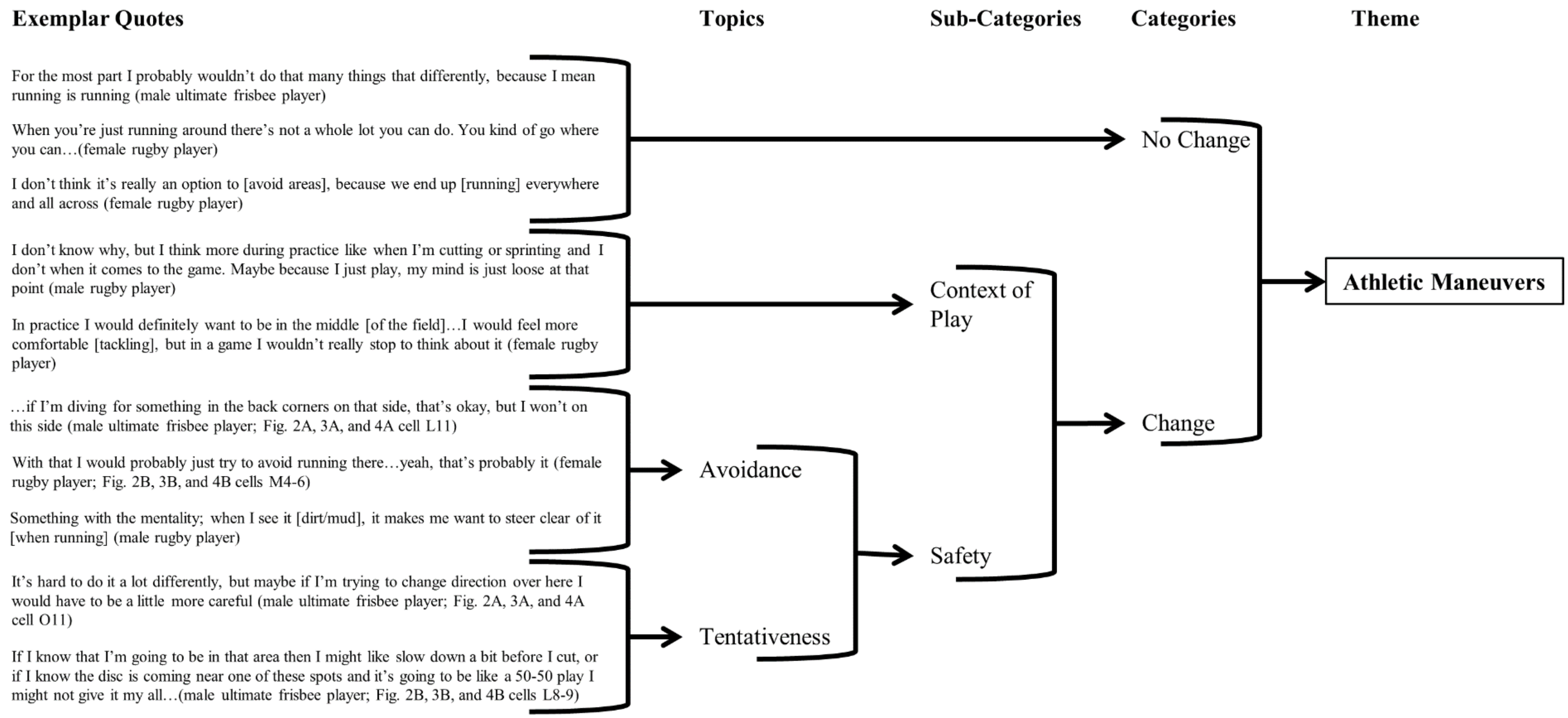

Figure 2.6 Hierarchy diagram of the theme 'athletic maneuvers'. Columns moving left to right illustrate the data (exemplar quotes from athletes), topics, categories, and ultimately the overarching theme.

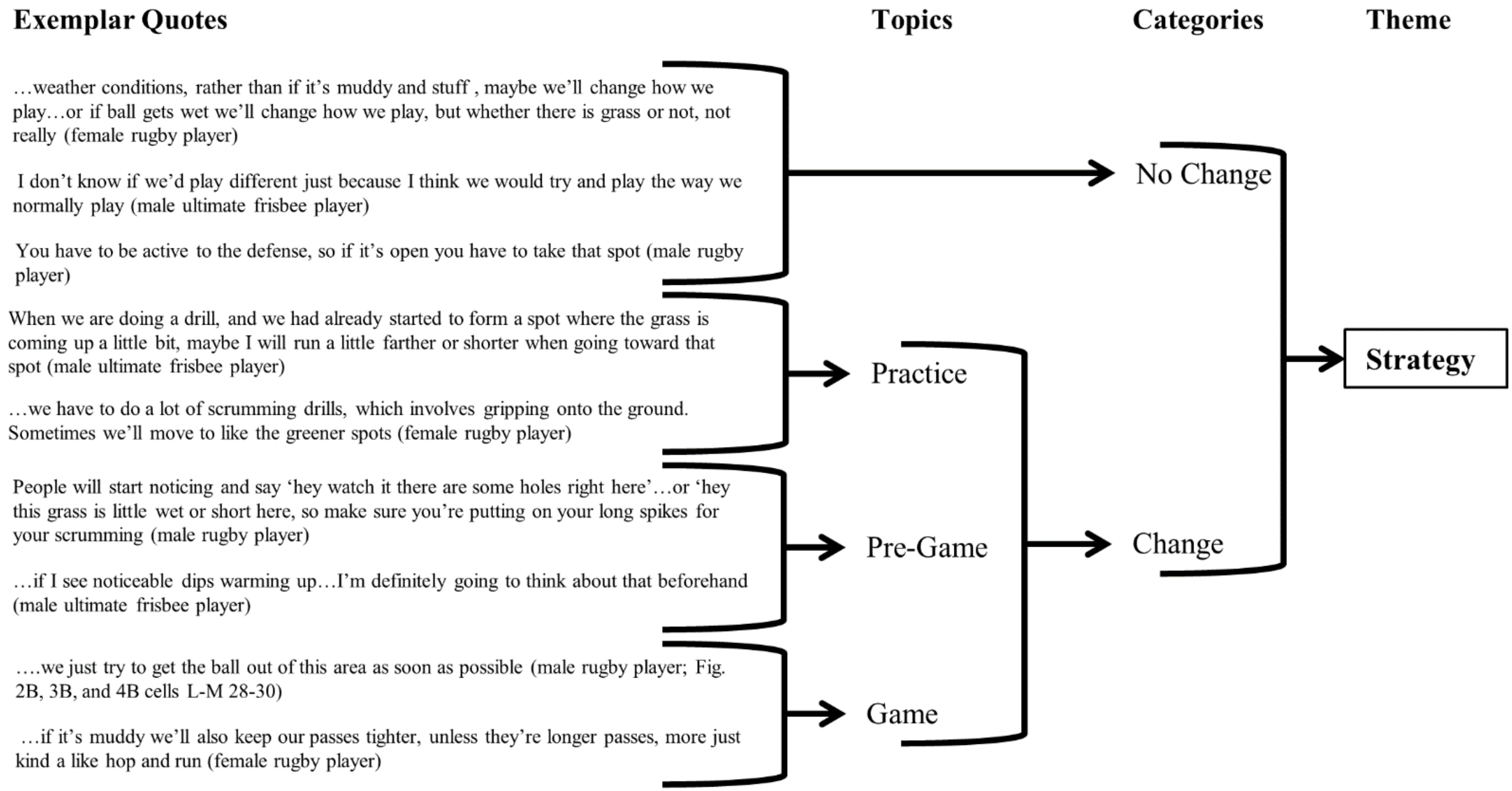

Figure 2.7 Hierarchy diagram of the theme 'strategy'. Columns moving left to right illustrate the data (exemplar quotes from athletes), topics, categories, and ultimately the overarching theme.

Appendix 2.1 Descriptive statistics of normalized difference vegetation index (NDVI), surface hardness, and turfgrass shear strength in the spring and fall.

	Min	Max	Range	Mean	SD	CV (%)
NDVI						
spring	0.22	0.72	0.50	0.46	0.12	26.1
fall	0.33	0.82	0.49	0.57	0.12	21.1
	———Gmax———					
Surface hardness						
spring	60.5	139.5	79.0	99.7	15.7	15.7
fall	49.0	151.0	102.0	84.7	18.1	21.4
	———Nm———					
Shear strength						
spring	3.5	20.8	17.3	8.0	3.8	47.5
fall	3.8	20.8	17.0	14.3	2.8	19.6

Abbreviations: Min, minimum; Max, maximum; SD, standard deviation; CV, coefficient of variability.

CHAPTER 3

DOES VARIABILITY WITHIN NATURAL TURFGRASS SPORTS FIELDS INFLUENCE GROUND-DERIVED INJURIES?[1]

[1]Straw, C.M., C.O. Samson, G.M. Henry, and C.N. Brown. Submitted to the *Journal of Sports Science*, 10/17/17.

Abstract

This study introduces a new methodology aimed at evaluating the potential relationship between within-field variations of turfgrass sports field properties and ground-derived athlete injuries. Collegiate Club Sport athletes self-reported ground-derived injuries over two years. Soil moisture, turfgrass quality, surface hardness, and turfgrass shear strength were quantified from their two home fields. Hot spot analysis identified significantly high (hot spots) and low (cold spots) values within the fields. Injury locations were compared to hot spot maps each month. Binomial proportion tests determined if there were differences between observed injury proportions and expected proportions. Twenty-three ground-derived injuries were reported overall. The observed injury proportions occurring in turfgrass quality cold spots [0.52 (95% CI 0.29-0.76)] and soil moisture hot spots [0.43 (95% CI 0.22-0.66)] was significantly higher than expected [0.20 ($P < 0.001$) and 0.21 ($P < 0.05$), respectively]. Most injuries in significant areas of turfgrass quality, soil moisture, and surface hardness were along edges of hot and cold spots. These results suggest a potential relationship between within-field variations and ground-derived injuries, particularly in transition areas between non-significant and significant high and low values. Future larger-scale studies can incorporate the reported methodology to validate this relationship and implement strategies that reduce ground-derived injuries.

Introduction

Sports field surfaces are considered an extrinsic risk factor for athlete injury (Petrass & Twomey, 2013; Rennie, Vanrenterghem, Littlewood, & Drust, 2016; Stiles, James, Dixon, & Guisasola, 2009). The majority of current literature investigating athlete-surface interactions has focused on natural turfgrass versus artificial turf fields (Fuller, Dick, Corlette, & Schmalz, 2007; Andersson, Ekblom, & Krustrup, 2008; Zanetti, Bignardi, Franceschini, & Audenino, 2013), while each field type has received minimal attention alone. Turfgrass sports fields can exhibit considerable within-field variations compared to artificial turf fields due to climatic conditions, field construction, field management, and foot traffic patterns from field usage (Caple, James, & Bartlett, 2012; Straw & Henry, 2017). Variations within a field could influence the playing surface predictability and require athletes to make abrupt or frequent adjustments. For example, changes in surface hardness can affect biomechanical loads and movement by athletes causing them to adjust leg stiffness when running (Ferris, Liang, & Farley, 1999; Stiles, Guisasola, James, & Dixon, 2011). The ability to quickly change leg stiffness helps an athlete maintain dynamic stability once field conditions change (Ferris et al., 1999; Rennie et al., 2016); conversely, we speculate the inability to do so may make them susceptible to injury. Furthermore, changes in traction can influence sudden stops and pivoting. This may leave athletes susceptible to falling (less traction) or having their foot "trapped" in the turfgrass and potentially injuring knee ligaments (too much traction) (Orchard, Chivers, Aldous, Bennell, & Seward, 2005).

To date, only five studies have compared objective field data to injury occurrence on turfgrass sports fields (Rennie et al., 2016). Each utilized a penetrometer (Orchard, 2001; Orchard et al., 2005; Takemura, Schneiders, Bell, & Milburn, 2007) or Clegg hammer (Twomey, Finch, Lloyd, Elliott, & Doyle, 2012a; Twomey, White, & Finch, 2012b) to measure surface hardness (from ≤20 locations in a field). These studies included several fields and compared injury incidence to averaged values (from measurement locations within and between fields) (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012b) or categories of magnitude (injuries were matched to nearest corresponding hardness measurement location on each field and compiled from all fields) (Twomey et al., 2012a). Information regarding within-field variations of individual fields was not provided in any study, nor were additional field properties (e.g. soil moisture, turfgrass quality, traction) that may contribute to injury (Petrass & Twomey, 2013). Disregarding within-field variations of field properties may obscure results by neglecting the influence of playing surface predictability.

Global positioning system-equipped data acquisitions are becoming prevalent in the turfgrass industry to obtain geo-referenced field data for the creation of spatial maps and identification of within-field variability (Caple et al., 2012; Straw & Henry, 2017). More intensive sampling than the aforementioned studies is required to detect small-scale spatial variations (Straw & Henry, 2017). Maps of field properties are currently used to suggest the concept of Precision Turfgrass Management (i.e. applying management inputs only where, when, and in the amount needed to potentially reduce management expenditures and improve field uniformity) (Carrow, Krum, Flitcroft, & Cline, 2010), but they may also be useful to evaluate the influence of within-field variations on injury occurrence. Therefore, we conducted a preliminary study to investigate whether a relationship between within-field variations and ground-derived injuries (i.e. any injury directly caused by the playing surface) exists. By doing so, we introduce an innovative methodology that may assist future prospective studies in identifying within-field variations of objectively measured field properties for comparison to ground-derived athlete injury locations in a field. Results could be used to implement Precision Turfgrass Management strategies that potentially improve field uniformity and decrease ground-derived injury occurrence.

Methods

A two year prospective study [each comprised of a fall (August-November) and spring (January-May) period] was conducted at a university in the southeast United States on Club and Recreational (Rec) fields. The fields are designated home fields for Competitive (Club) Sports teams, but the Rec field also hosts non-sporting events and is open for leisure. The fields each had hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) x *C. transvaalensis Burtt-Davy*] (mowed at ~2.5 cm); however, the Club field was constructed on a 25 cm sand cap with clay beneath and the Rec field was constructed on native soil (sandy loam). The study began at the Club field (85 x 174 m) in fall 2015 (mid-August to mid-September), but moved to the Rec field (67 x 122 m) due to team scheduling changes. It remained at the Rec field throughout the study's duration. The Club field was included back into the study spring 2017; although a synthetic field had been built adjacent, which decreased the size of the turfgrass field (91 x 122 m). The Club field was also overseeded with perennial ryegrass (*Lolium perenne* L.) during spring 2017. Both fields had irrigation systems to supplement rainfall during dry periods (rainfall and temperature data provided in Appendix 3.1).

Participants were Club Sports athletes from the university's men's and women's rugby and ultimate frisbee teams, as well as the women's lacrosse team (Table 3.1). Some were experienced in their particular sport, but others were playing for the first time. Club Sports are student-led teams that compete against other colleges at the state, regional, and national level. Games and practices are year-round for all Club Sports teams. All competition took place on one field until the Club field was reintroduced in spring 2017. During that time, rugby teams used solely the Rec field, ultimate frisbee teams used solely the Club field, and the women's lacrosse team used both. The local Institutional Review Board approved the study and informed consent was received from all athletes prior to participation. All athletes reported using cleats during games and practice.

Weekly online questionnaires were emailed to athletes to identify if an injury occurred during the previous week and to determine participation level. Injury was defined for the athletes as "A physical complaint (pain, discomfort, etc.) that resulted from your team's practice or competition, whether you sought medical treatment or not" (Timpka et al., 2014). Questions regarding injury (e.g. anatomical location, injury type, mechanism of injury, contact or non-contact) used previous methodologies as guidelines (Hootman, Dick, & Agel, 2007; Timpka et al., 2014; Yang, Tibbetts, Covassin, Cheng, Nayar, & Heiden, 2012). A geo-referenced alphanumeric grid was created over each field using ArcMap (ESRI, Redlands, CA) and provided in the questionnaires to report where in the field an injury occurred (Figure 3.1A). Corresponding letter and number signs hung along a fence in the fields to aid the athletes. Upon the study's completion, triangular consensus validation was conducted between three investigators to discuss the validity of the self-reported injuries and to decide which injuries to keep for analysis (Patton, 1990). Only ground-derived injuries were considered, excluding such injuries caused by contact with another athlete or other objects. We included acute and overuse injuries, since contact with the ground was either acute or repetitive over time. Based on athletes' responses, the vast majority of their physical activity was completed on these fields.

Soil moisture (volumetric water content) and turfgrass quality (normalized difference vegetation index; NDVI) were measured either weekly or bi-weekly with a mobile data acquisition unit: the Toro Precision Sense 6000 (PS6000; The Toro Company, Bloomington, MN) (Figure 3.2A) (Straw & Henry, 2017). The PS6000's sampling head contained two stainless steel probes connected to a capacitance sensor used to measure water content of the soil at a 10 cm depth (Dean, Bell, & Baty, 1987). A GreenSeeker Model 500 active sensor (Trimble, Sunnyvale, CA) mounted to the rear of the PS6000 measured NDVI (Bell, Martin, Koh, & Han, 2009). Normalized difference vegetation index has been used as an objective indication of visual quality and density of turfgrass canopies (Trenholm, Carrow, & Duncan, 1999).

Surface hardness and turfgrass shear strength (i.e. rotational traction) of the fields were measured bi-weekly during the study with handheld data acquisitions. A Clegg Impact Tester (Lafayette Instrument Co., Lafayette, IN) measured surface hardness (Figure 3.2B). It had a 2.25 kg missile with an accelerometer at the end, which was dropped once through a guide tube from a height of 45 cm to measure deceleration on impact reported as gravities (g) [American Society for Testing and Material (ASTM) F1702, 2010]. The Turf-Tec Shear Strength Tester (Turf-Tec Int., Tallahassee, FL) measured turfgrass shear strength (Figure 3.2C). This device had a shear vane foot that was inserted into the soil, and then a torque wrench handle was turned steadily (manufacturer recommendation). The highest torque (Nm) until the turfgrass began to tear was measured by a follower needle on the wrenches gauge.

Soil moisture was measured with the PS6000 using a ~4.6 x 2.4 m sampling grid (~765-1,295 samples depending on field). As the PS6000 traversed the fields, every third measurement was flagged for handheld data collection; therefore, surface hardness and turfgrass shear strength were measured using a ~4.6 x 7.3 m sampling grid (~255-324 samples depending on field). Surface hardness and turfgrass shear strength were each measured predominately by one experienced tester during the entirety of the study. Rater reliability was not tested before data collection because measurements could not be repeated at the same location without altering results. Since the NDVI sensor outputs data at a superabundant rate, turfgrass quality data were manipulated to correspond with the handheld sample locations. A NovAtel Smart-AG^{TM} GPS (NovAtel, Inc., Alberta, Canada) with sub-meter real-time accuracy was attached to the PS6000 to geo-reference all data.

Hot spot maps to identify within-field variability of each field property were created in ArcMap by first interpolating the geo-referenced data points (from each data collection) via ordinary kriging (Cressie, 2015). Kriged maps were saved as raster maps and the "zonal statistics as table" tool calculated the average value of pixels within all cells of the alphanumeric grid. Data from each cell were averaged by month and added to the grid's attribute table. Hot spot maps were created for a respective field property each month using the "hot spot analysis" tool to calculate the G_i* statistic for individual cells in the grid (Getis & Ord, 1992). A positive and significant G_i* indicates a "hot" spot (i.e. a cell with a high value relative to all cells) and a negative and significant G_i* indicates a "cold" spot (i.e. a cell with a low value relative to all cells) (Figure 3.1B). Injury locations from a given month were compared to that month's hot spot maps. Most injuries were reported within a single cell, but a few were reported in larger areas. When the number of cells reported was ≤4, those cells and their immediate neighbors were considered to account for potential error in reporting. The location was deemed as a hot or cold spot if at least one cell within the area was significant.

Lastly, binomial proportion tests were conducted in RStudio (RStudio, Inc., Boston, MA) for all field properties to evaluate if the observed proportions (i.e. proportion of injuries that occurred in a hot and/or cold spot) were similar to the expected proportions (i.e. the proportion of the field that was a hot and/or cold spot). The monthly hot and/or cold proportions from the fields were averaged in order to have an overall expected proportion for each field property. Only months when an injury occurred were considered.

Results

Twenty-three ground-derived injuries were reported (Table 3.2). Several occurred in practice (16/23; 70%), rather than games (6/23; 26%), and one was reported as "other". They were mainly to the lower extremities (17/23; 74%), but some were to the upper extremities (4/23; 17%) and the head or face (2/23; 9%). Athletes returned to play the same day 65% (15/23) of the time and only 17% (4/23) sought medical attention after being injured. The majority of athletes injured had a similar previous injury (14/23; 61%) and three of them suffered multiple injuries during the study (Table 3.2; injuries #5 and #13, injuries #6 and #19, and injuries #12, #14, and #15 are the same person, respectively).

The highest proportion of injuries occurred within a hot or cold spot of turfgrass quality (15/19; 79%), followed by soil moisture (16/21; 76%), and then surface hardness and turfgrass shear strength (13/23; 57%) (Table 3.2; hot spot maps of each measured field property with injury locations are provided in Appendices 3.2-3.5). The observed proportions of injuries occurring in turfgrass quality and soil moisture hot and cold spots [0.79, (95% CI 0.54-0.94) and 0.76 (95% CI 0.53-0.92), respectively] were significantly different than the expected proportions (0.35 and 0.43, respectively) ($P < 0.01$). The observed proportion of injuries occurring in turfgrass quality hot spots was not significantly different than the expected proportion, but the observed proportion of injuries occurring in turfgrass quality cold spots [0.52 (95% CI 0.29-0.76)] was significantly different than expected (0.20) ($P < 0.001$). Conversely, the observed proportion of injuries occurring in soil moisture hot spots [0.43 (95% CI 0.22-0.66)] was significantly different than expected (0.21) ($P < 0.05$); however, the observed proportion of injuries occurring in soil moisture cold spots was not significantly different. There were no significant differences between observed and expected proportions with respect to surface hardness and turfgrass shear strength hot and/or cold spots.

A trend of injuries occurring along edges of hot and cold spots (i.e. cells within the reported area were not all significant) was observed with respect to turfgrass quality (11/15 injuries), soil moisture (14/16 injuries), and surface hardness (9/13 injuries). Approximately half of the injuries occurring in turfgrass shear strength hot or cold spots were either along an edge (6/13 injuries) or fully within (i.e. cells within the reported area were all significant; 7/13 injuries).

Discussion

This preliminary study is the first to investigate the influence of within-field variability on ground-derived athlete injury occurrence. Previous studies associating objectively measured ground conditions to injuries were limited to surface hardness and did not consider within-field variations of individual fields (Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012b). Those studies provide minimal evidence of a significant relationship between surface hardness and injury occurrence. A non-significant trend was observed towards increased risk of ACL injury on harder grounds in Australian Football (Orchard, 2001), as well as an increased risk for injury (at any body region) in low/normal (30-69 g) and unacceptable high (>120 g) hardness categories in community-level Australian football (Twomey et al., 2012a). Our within-field hardness levels varied from 39 to 123 g (during months when injuries occurred; descriptive statistics of each field property each month provided in Appendix 3.6); however, the observed proportion of ground-derived injuries that occurred in hot and cold spots was not different than the expected proportion, indicating there was not a higher or lower injury occurrence in areas of significantly high or low hardness values within the fields.

Our observed proportion of ground-derived injuries was significantly higher than the expected proportion in soil moisture hot spots and turfgrass quality cold spots, indicating there was a higher injury occurrence in these areas. The observed and expected proportions for turfgrass shear strength were not different, indicating there was not a higher or lower injury occurrence within hot or cold spots of this field property. Since this is the first preliminary study to associate injury data with objectively measured soil moisture, turfgrass quality, and turfgrass shear strength data we cannot compare to previous studies. Ground conditions in injury studies have typically been subjective and placed into broad categories (e.g. “good”, “muddy”, or “slippery”) with minimal details provided on where or how they were obtained (Andresen, Hoffman, & Barton, 1989; Gabbett, Minbashian, & Finch, 2007; Ramirez, Schaffer, Shen, Kashani, & Kraus, 2006). Future studies must use objective measurements so methodologies are repeatable and results between studies can be compared (Petrass & Twomey, 2013; Rennie et al., 2016).

Other ground-related studies have primarily considered the causation of injury related to surface hardness and traction (Orchard et al., 2005; Takemura et al, 2007; Twomey et al., 2012a); however, we observed an increased injury occurrence in soil moisture hot spots and turfgrass quality cold spots, which suggests that these field properties require further exploration. All field properties we measured are correlated with one another to some degree (Holmes & Bell, 1986; Straw & Henry, 2017), so the increased injury occurrence in areas of high soil moisture and low turfgrass quality may be more related to their combined interactions with other field properties, rather than themselves individually. This stresses the importance of evaluating more than one field property, because the occurrence associated with different types of injuries may vary between field properties or combinations of field properties (Twomey et al., 2012a). Due to our low injury numbers, a connection between injury type and combinations of field properties was not made. It should be noted that NDVI measurements (i.e. turfgrass quality) appeared to be influenced by field dormancy. We removed injuries that occurred during dormant months (January and February) and our results were generally unaffected. Nonetheless, future larger-scale studies that use NDVI should consider how it is influenced between periods when the turfgrass is actively growing and dormant.

We hypothesized changes within a field may lead to increased injury occurrence due to uncertainty of the playing surface. The majority of injuries that occurred in significantly high and low areas of soil moisture, turfgrass quality, and surface hardness were along the edges of hot and cold spots. This implies an increased injury occurrence may happen when an athlete transitions from an “average” area (i.e. non-significant area) to a hot or cold spot of these field properties, as opposed to an injury occurring fully within one of these areas. Additional research is warranted with a larger injury sample size and more fields to further test the hypothesis.

Other limitations should be mentioned. First, the optimum frequency of data collection and number of field properties to measure is unknown. This study is an example of how field properties may change between months (both their magnitude and variability), but it is possible changes could occur between weeks or even days (Straw & Henry, 2017); therefore, finding a balance between the cost and time associated with GPS measurements and quality of data must be determined. Next, the overall weekly average response rate of the questionnaire was moderate (76%), but athletes may not have reported all injuries or exact locations of injury. Future research should have a trained professional assess injuries and geo-reference their locations *in-*

situ as they occur. Global positioning systems that are already incorporated into athletic gear to monitor movement patterns and intensity during play may be of assistance (Gray, Jenkins, Andrews, Taaffe, & Glover, 2010; Varley, Fairweather, & Aughey, 2012).

Conclusions

This preliminary study investigated if there was an association between within-field variability and ground-derived injuries on recreational-level sports fields. We introduced a methodology to more accurately match injury locations with objective site-specific field data. Injury numbers were low, but results demonstrate a higher occurrence of ground-derived injury was evident in areas of significantly high soil moisture and low turfgrass quality within the study fields. Notably, most injuries that happened in significantly high or low areas of turfgrass quality, soil moisture, and surface hardness occurred along edges of hot and cold spots. These results demonstrate that future studies should consider within-field variations of natural turfgrass sports field properties when researching the etiology of ground-derived injuries, because there could be a potential relationship. This includes incorporating several objective field measures and evaluating their interactions in relation to injury locations in a field. Management strategies should also focus on improving field uniformity, perhaps with Precision Turfgrass Management or by better monitoring and modifying field use (e.g. set time limits or rotate practice drills).

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Table 3.1 Participant numbers and their demographic means and standard deviations.

	Sport/gender	Age	Height (cm)	Mass (kg)
Year 1				
	Rugby (fall and spring[a])			
	Male (n = 12)	20.6 ± 0.8	178.8 ± 7.6	85.6 ± 17.8
	Female (n = 13)	20.5 ± 1.5	165.7 ± 4.4	75.4 ± 15.5
	Ultimate Frisbee (spring only)			
	Male (n = 8)	21.4 ± 2.8	178.4 ± 5.6	69.9 ± 7.4
	Female (n = 7)	20.4 ± 1.6	166.5 ± 5.4	61.0 ± 8.6
	Total[b] = 40			
Year 2				
	Ultimate Frisbee (fall and spring)			
	Male (n = 14)	20.1 ± 2.0	184.2 ± 5.5	77.3 ± 7.6
	Female (n = 4)	20.0 ± 0.8	166.3 ± 3.2	68.5 ± 10.7
	Rugby (spring only)			
	Female (n = 12)	20.2 ± 1.6	165.7 ± 2.6	70.2 ± 9.1
	Lacrosse (spring only)			
	Female (n = 16)	20.4 ± 0.9	168.8 ± 4.4	66.1 ± 5.8
	Total = 46			

[a] Year 1 and 2 each had a fall (August-November) and spring (January-May) study period.

[b] The total number of participants each year is independent (i.e. athletes that participated both years re-consented in year 2 and are included in year 2 totals).

Table 3.2 Ground-derived injuries and whether they occurred in a hot or cold spot (i.e. areas of significantly high or low values, respectively) of measured field properties.

	Injury #	Sport	Gender	Month	Field[a]	Injury location	Injury type	Category	Hot/cold SM[b]	Hot/cold TQ	Hot/cold SH	Hot/cold TSS
Year 1												
	1	R	F	August	Club	Knee	Pain and swelling	Overuse	Cold	Cold	Hot	
	2	R	M	September	Club	Hand	Tendon	Trauma	Cold	Cold		Cold
	3	R	M	September	Club	Shoulder/clavicle	Sprain	Trauma	Cold	Cold	Hot	Cold
	4	R	F	September	Club	Ankle	Sprain	Overuse	Cold	Cold	Hot	Cold
	5	R	F	September	Club	Heel	Contusion	Trauma	Hot	Hot	Cold	Hot
	6	R	F	October	Rec	Knee	Sprain	Trauma	Cold			Hot
	7	UF	F	January	Rec	Shins	Shin splints	Overuse	Cold	Hot	Hot	Cold
	8	UF	M	January	Rec	Hand	Contusion	Trauma		Cold		Hot
	9	R	F	February	Rec	Ankle	Sprain	Trauma	Cold	Hot	Hot	
	10	UF	M	February	Rec	Knee	Tendon	Overuse		Cold		
	11	UF	F	February	Rec	Ankle	Instability	Overuse	Hot	Hot		Cold
	12	UF	M	February	Rec	Hand	Sprain	Trauma	Hot	Cold		
	13	R	F	February	Rec	Head/face	Contusion	Trauma	Hot	Cold	Cold	Cold
	14	UF	M	March	Rec	Foot	Sprain	Trauma		Cold		
	15	UF	M	March	Rec	Foot	Sprain	Trauma	Hot	Hot	Cold	
	16	UF	M	April	Rec	Achilles tendon	Strain	Trauma	Hot	Cold		
Year 2												
	17	UF	F	August	Rec	Knee	Sprain	Overuse	Hot		Hot	Cold
	18	R	F	January	Rec	Head	Sprain	Trauma	N/A[c]	N/A	Cold	
	19	R	F	January	Rec	Elbow	Contusion	Trauma	N/A	N/A	Hot	Cold
	20	UF	M	January	Club	Ankle	Sprain	Trauma	Hot	N/A	Cold	Cold
	21	UF	F	January	Club	Ankle	Sprain	Trauma		N/A		Hot
	22	L	F	February	Club	Knee	Sprain	Trauma				
	23	R	F	February	Rec	Ankle	Sprain	Trauma	Hot		Cold	

Abbreviations: R, rugby; UF, ultimate frisbee; L, lacrosse; F, female; M, male; SM, soil moisture; TQ, turfgrass quality; SH, surface hardness; TSS, turfgrass shear strength.

[a] The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2.

[b] Empty cells indicate injury occurred in non-significant area.

[c] Not applicable, because data were not collected due to sampling device malfunction.

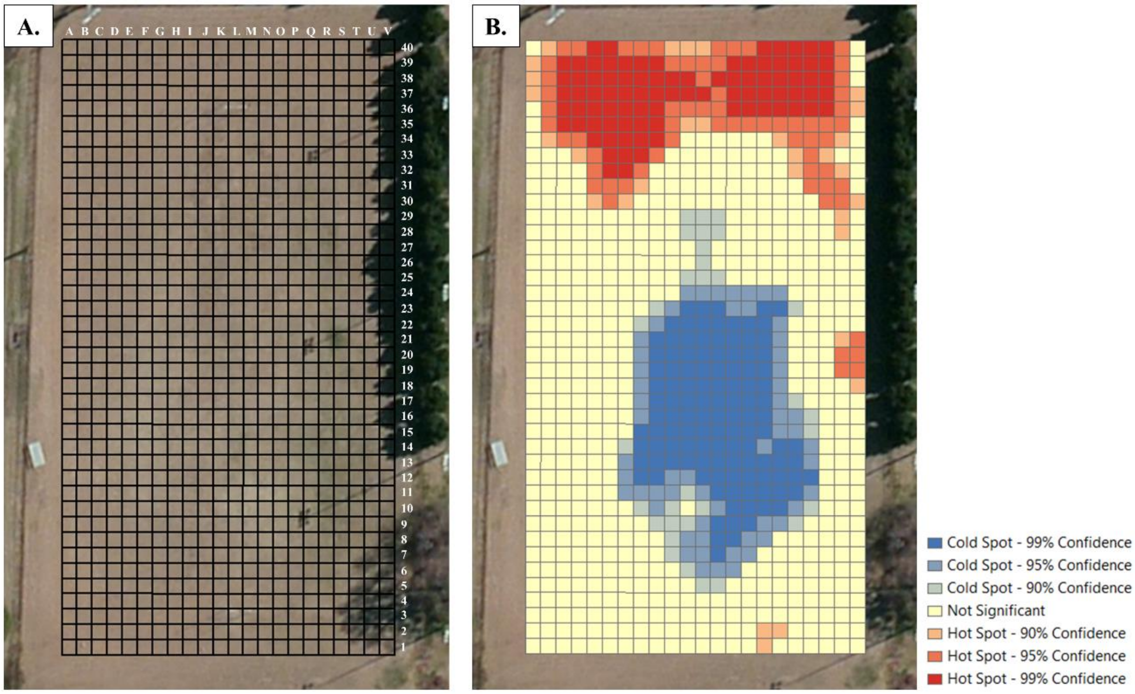


Figure 3.1 A) An example of the geo-referenced alphanumeric grid (3 x 3 m cells) that was provided to athletes in questionnaires to report where injuries occurred on the field. Corresponding letter and number signs hung along a fence in the fields. B) An example of a hot spot map. Red and blue cells represent significantly high and low values, respectively, within the field. Yellow cells are considered “average” values.

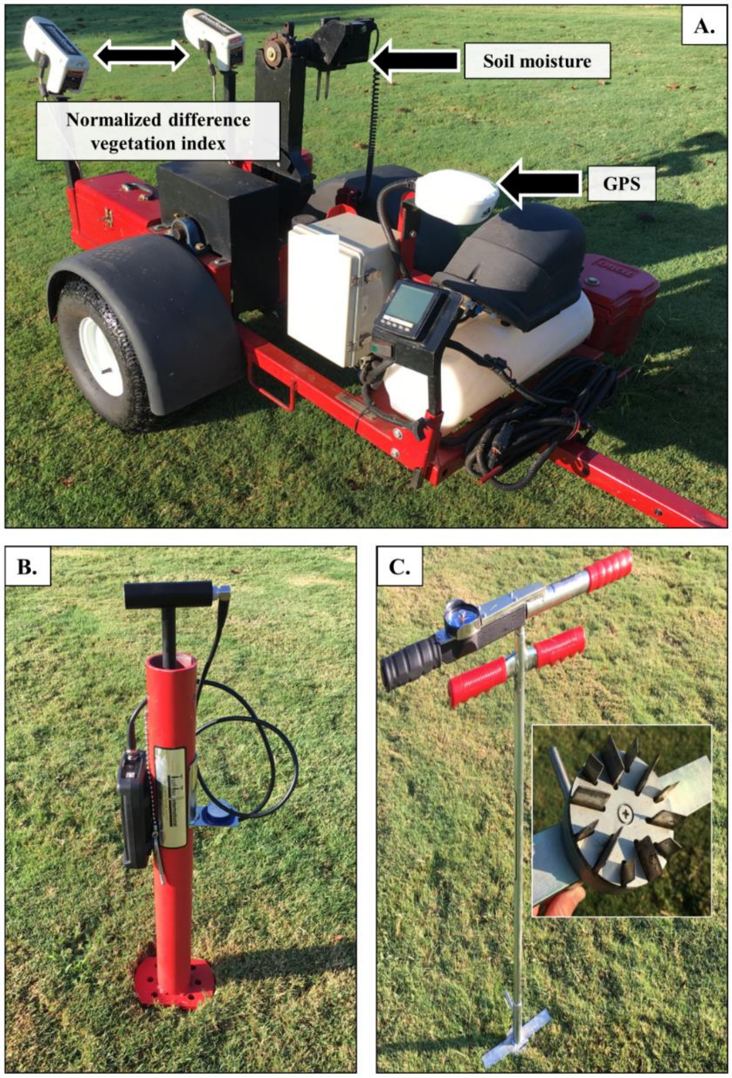
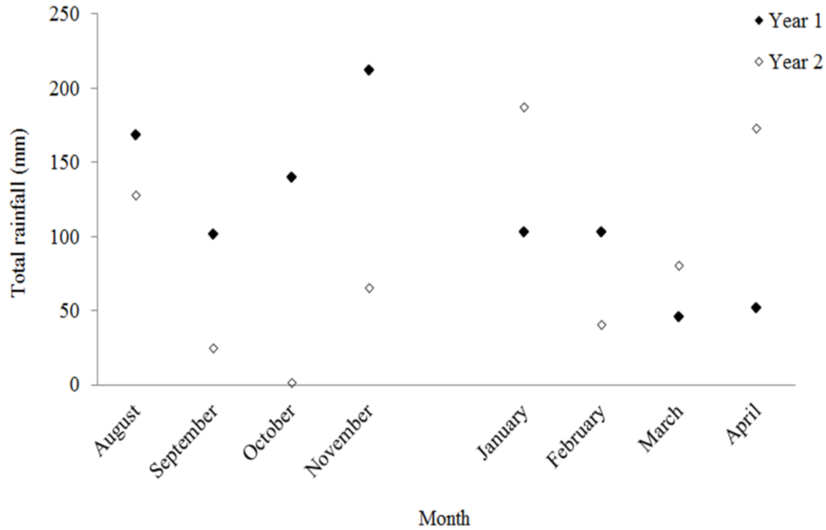
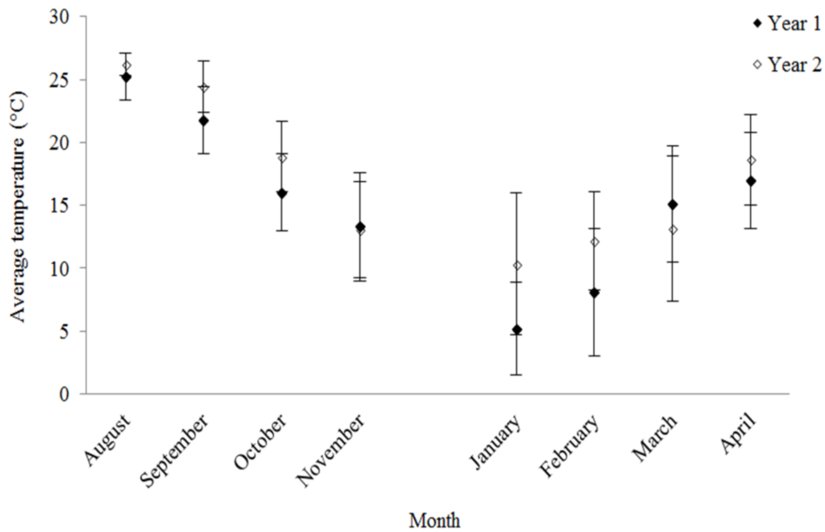


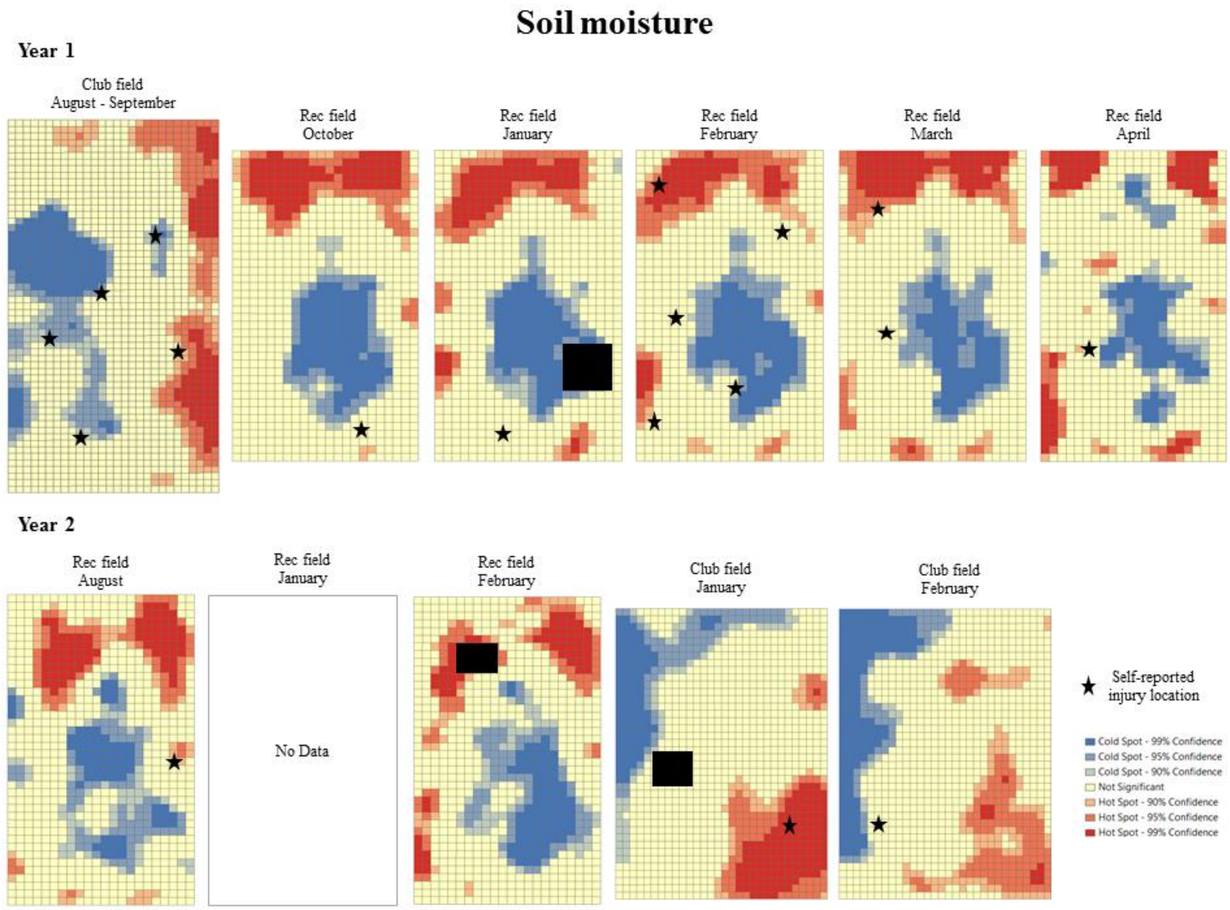
Figure 3.2 Sampling devices used for objectively measuring field properties: A) The Precision Sense 6000 used for measuring soil moisture (volumetric water content) and turfgrass quality (normalized difference vegetation index), as well as geo-referencing all data; B) A Clegg hammer used for measuring surface hardness; C) The Turf-Tech Shear Strength Tester used for measuring turfgrass shear strength.

Appendix 3.1 Total rainfall amount (top) and average temperature (bottom; SD error bars) during each month of the study.

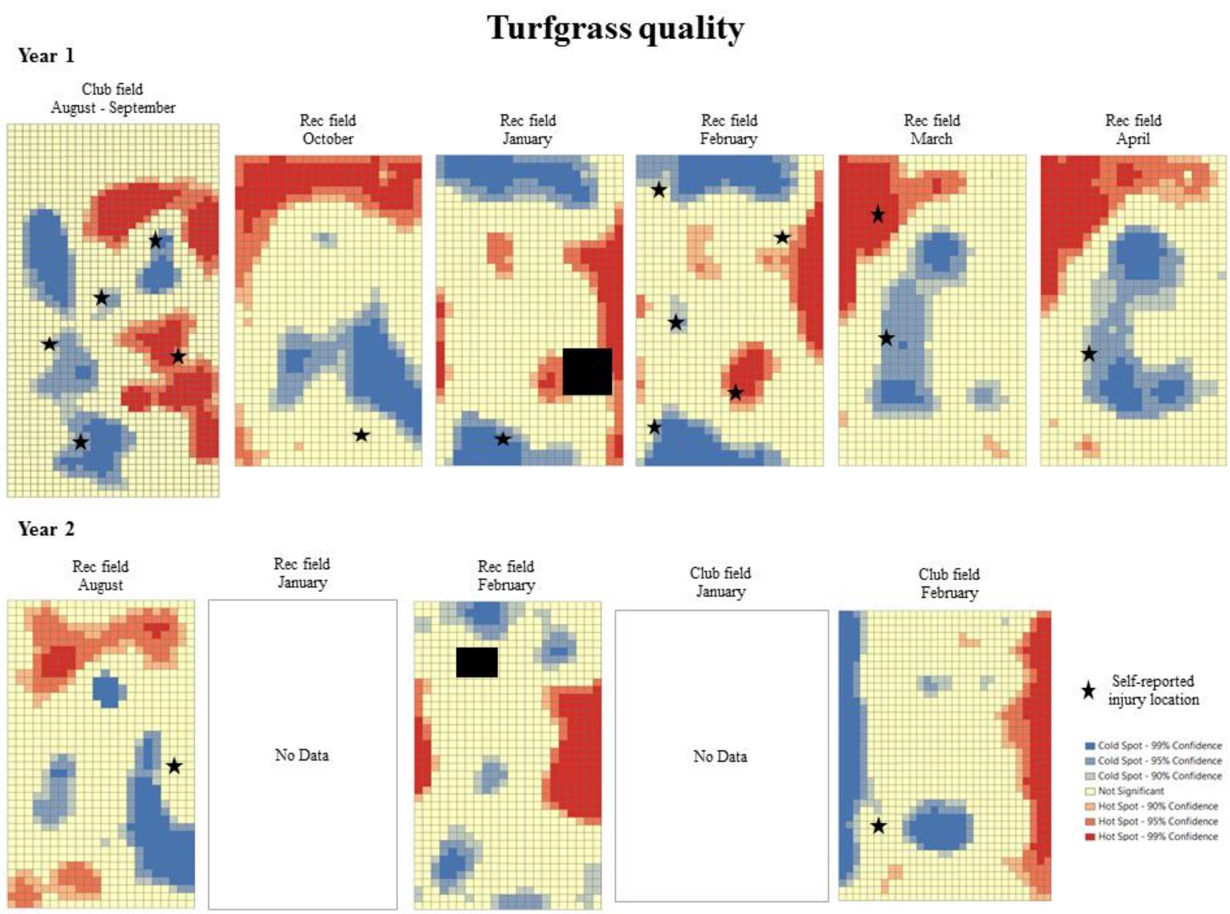




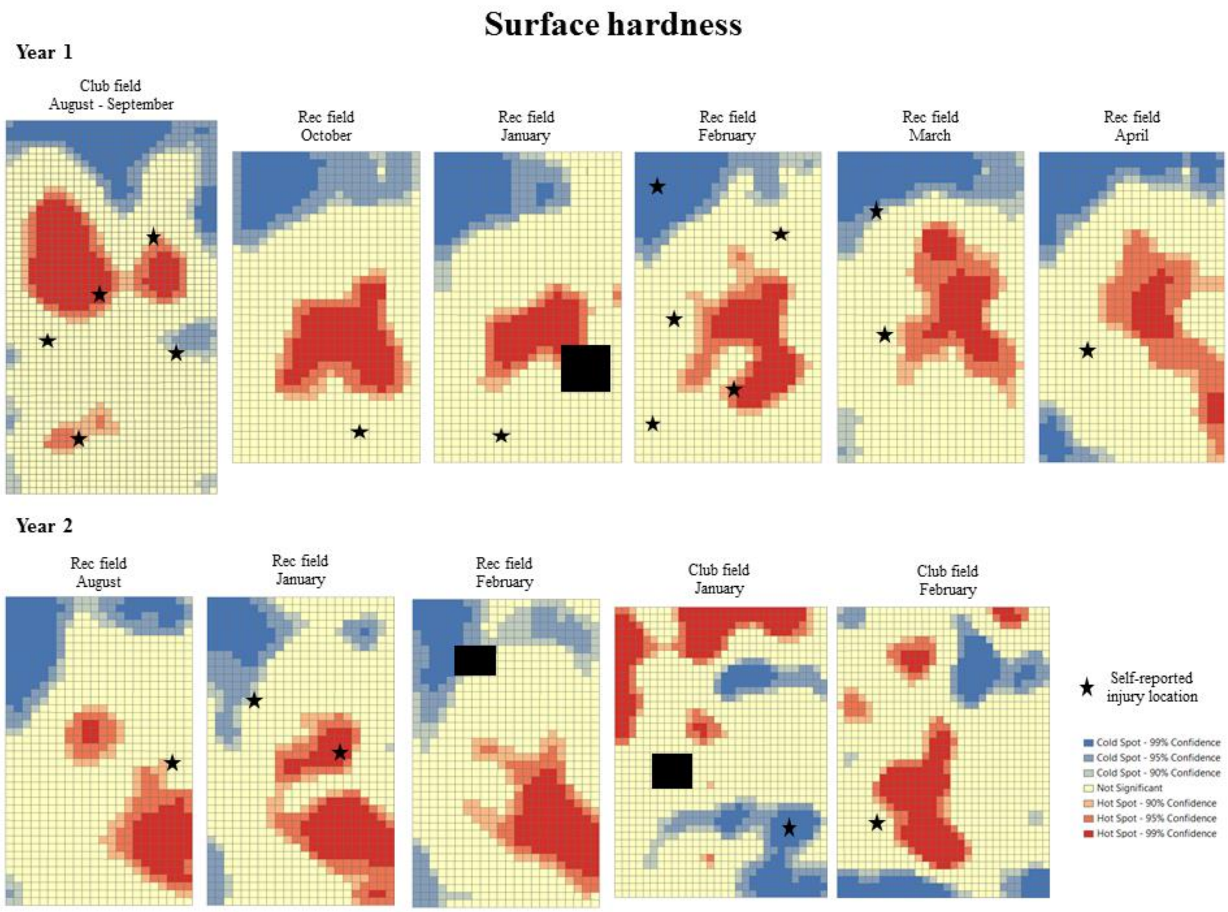
Appendix 3.2 Hot spot maps of soil moisture (volumetric water content) with self-reported injury locations (all ground-derived). Red and blue cells indicate areas of significantly high and low values, respectively, within the fields. Yellow cells are considered areas of "average" values. *Notes:* Only hot spot maps of months when an injury occurred are presented. The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2. The overall grid dimension was reduced at the Club field from year 1 to year 2 due to installation of a synthetic turf field in the northern portion of the field. Data were not collected in January due to device malfunction. Black boxes are self-reported injury locations that were ≥4 cells.



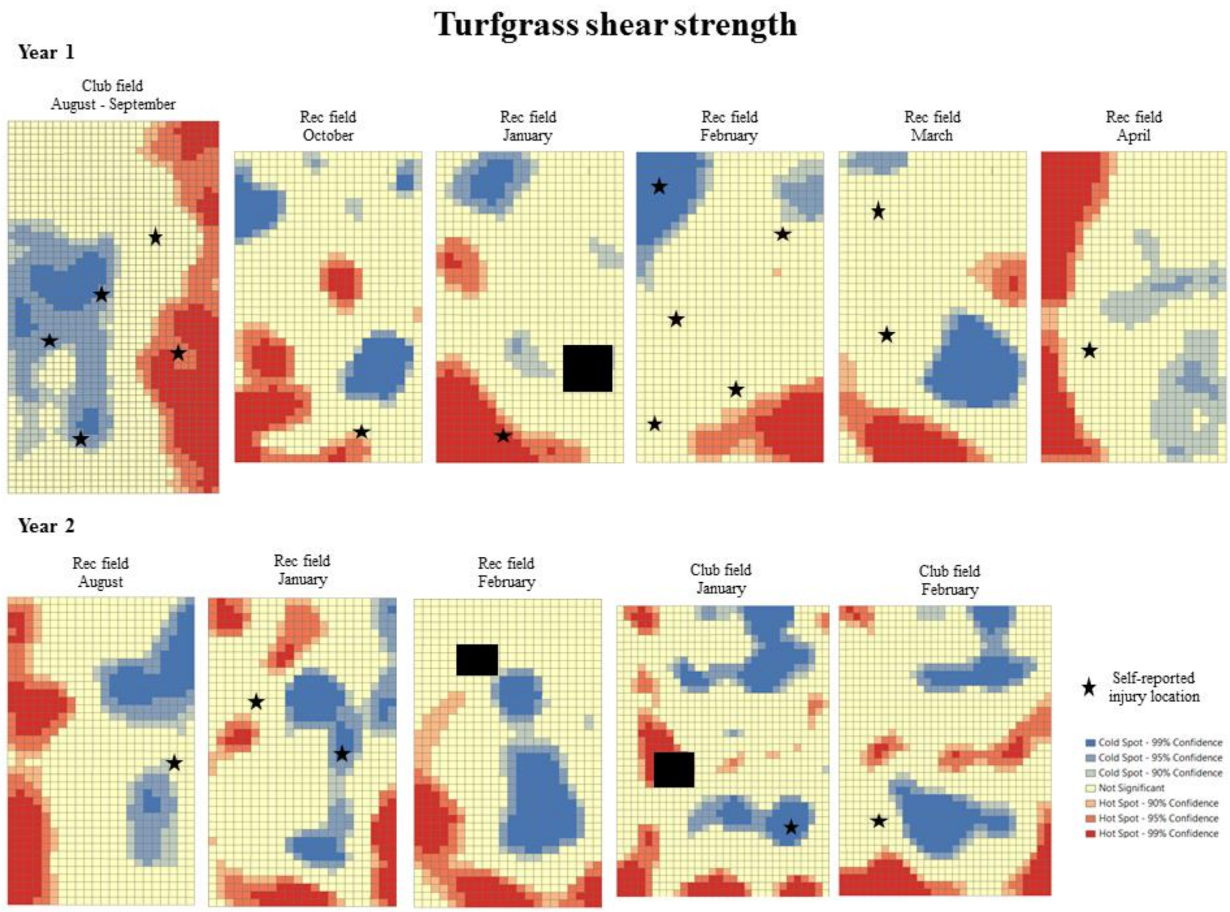
Appendix 3.3 Hot spot maps of turfgrass quality (normalized difference vegetation index) with self-reported injury locations (all ground-derived). Red and blue cells indicate areas of significantly high and low values, respectively, within the fields. Yellow cells are considered areas of "average" values. *Notes:* Only hot spot maps of months when an injury occurred are presented. The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2. The overall grid dimension was reduced at the Club field from year 1 to year 2 due to installation of a synthetic turf field in the northern portion of the field. Data were not collected in January due to device malfunction. Black boxes are self-reported injury locations that were ≥4 cells.



Appendix 3.4 Hot spot maps of surface hardness with self-reported injury locations (all ground-derived). Red and blue cells indicate areas of significantly high and low values, respectively, within the fields. Yellow cells are considered areas of “average” values. *Notes:* Only hot spot maps of months when an injury occurred are presented. The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2. The overall grid dimension was reduced at the Club field from year 1 to year 2 due to installation of a synthetic turf field in the northern portion of the field. Black boxes are self-reported injury locations that were ≥4 cells.



Appendix 3.5 Hot spot maps of turfgrass shear strength with self-reported injury locations (all ground-derived). Red and blue cells indicate areas of significantly high and low values, respectively, within the fields. Yellow cells are considered areas of "average" values. *Notes:* Only hot spot maps of months when an injury occurred are presented. The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2. The overall grid dimension was reduced at the Club field from year 1 to year 2 due to installation of a synthetic turf field in the northern portion of the field. Black boxes are self-reported injury locations that were ≥4 cells.



Appendix 3.6 Descriptive statistics for each field property.

	Field and month[a]	Soil moisture (%)			Turfgrass quality			Surface hardness (g)			Turfgrass shear strength (Nm)		
		Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD
Year 1													
	Club field												
	August – September	15.2	27.5	21.9 ± 2.4	0.49	0.66	0.58 ± 0.3	66.5	106.7	86.3 ± 7.9	4.7	14.1	9.0 ± 2.7
	Rec field												
	October	29.5	39.9	34.5 ± 2.4	0.47	0.83	0.68 ± 0.09	47.0	85.6	65.8 ± 9.0	11.8	17.5	15.1 ± 0.9
	January	32.8	41.1	37.3 ± 2.2	0.16	0.29	0.20 ± 0.03	38.6	70.8	54.3 ± 6.4	9.8	14.6	11.3 ± 0.9
	February	30.0	41.0	35.9 ± 2.5	0.19	0.30	0.24 ± 0.02	41.5	86.8	62.9 ± 9.5	10.7	16.5	13.8 ± 1.0
	March	25.3	37.5	31.0 ± 2.4	0.24	0.49	0.32 ± 0.05	46.1	92.5	71.4 ± 11.4	9.4	15.4	13.0 ± 1.1
	April	20.3	28.3	23.7± 1.6	0.22	0.70	0.44 ± 0.12	64.3	122.6	99.7 ± 13.2	4.5	15.9	8.0 ± 3.2
Year 2													
	Rec field												
	August	33.2	42.2	37.1 ± 2.0	0.70	0.85	0.81 ± 0.03	49.7	74.9	65.2 ± 5.7	10.8	16.3	13.1 ± 1.2
	January	N/A[b]	N/A	N/A	N/A	N/A	N/A	50.7	92.9	72.0 ± 9.0	10.6	18.9	15.4 ± 1.5
	February	26.0	37.4	31.6 ± 2.5	0.19	0.27	0.22 ± 0.02	49.3	108.2	76.6 ± 12.7	12.0	17.9	15.1 ± 1.2
	Club field												
	January	24.8	31.7	28.8 ± 1.5	N/A	N/A	N/A	57.8	90.4	70.7 ± 6.7	8.6	25.5	17.9 ± 3.1
	February	12.7	28.3	22.8 ± 3.7	0.45	0.83	0.65 ± 0.08	79.6	100.6	90.3 ± 3.9	12.6	26.5	19.0 ± 2.8

Note: Only summary statistics of months when a ground-derived injury occurred are presented.

[a] The study was initiated year 1 in mid-August at the Club field, and then moved early September to the Rec field; therefore, data from this time period at the Club field were combined. The study continued at the Rec field throughout duration, but the Club field was included back into the study beginning January of year 2.

[b] Not applicable, because data were not collected due to sampling device malfunction.

CHAPTER 4

SPATIOTEMPORAL RELATIONSHIP OF PLANT AND SOIL PROPERTIES IN NATURAL TURFGRASS SPORTS FIELDS[1]

[1]Straw, C.M., R.A. Grubbs, R.N. Carrow, and G.M. Henry. Submitted to *Precision Agriculture,* 08/18/2017.

Abstract

Variations of plant and soil properties in turfgrass sports fields may influence playing quality and athlete injury risk. This study investigates the spatiotemporal relationship of several properties to aid in efficient sampling for spatial map creation to potentially improve field uniformity with precision turfgrass management (PTM). Correlation coefficients and spatial maps were utilized to evaluate the spatiotemporal relationship of several properties in two sports fields comprised of sandy loam and sand capped soils before and after irrigation. Soil moisture (volumetric water content; VWC), soil compaction (penetration resistance), turfgrass vigor (normalized difference vegetation index; NDVI), surface hardness, and turfgrass shear strength data were obtained before and after irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay). Minimal changes in strength of relationships and spatial distributions were observed from before irrigation to after irrigation. Several significant relationships between properties were observed, although significance did not always result in comparable spatial distributions. Significant relationships and similar spatial distributions on the native soil field were not always the same on the sand capped field. Volumetric water content had the most similar spatial distribution with other properties in the native soil field. Spatial distributions of penetration resistance, NDVI, and surface hardness were similar in both fields. Depending on the objective, sampling and map creation of only one of these key properties may be necessary to predict the spatial distribution of other properties for PTM applications on sports fields.

Introduction

Plant and soil properties of natural turfgrass sports fields may influence playing quality (e.g. ball roll and bounce) (Bell and Holmes 1988; Canaway et al. 1990; Baker 1991) and athlete injury risk (i.e. injuries caused by the ground) (Orchard 2001; Takemura et al. 2007; Twomey et al. 2012). The quantification of these surface properties (e.g. soil moisture, soil compaction, surface hardness, and turfgrass shear strength) can be collectively called performance testing. In the sports turf industry, performance testing involves defining the surface properties that influence ball- and athlete-surface interactions (Bell et al. 1985; Baker and Canaway 1993; Baker 1999; Aldahir and McElroy 2014). Performance testing data may be used to assess field quality, create playing standards, guide management decisions, or conduct research (McAuliffe 2008; Bartlett et al. 2009; Carrow et al. 2010).

To-date, most *in-situ* performance testing research has used minimal sampling sizes (<10 locations on a field) and descriptive statistics to analyze generated data (Holmes and Bell 1986; McClements and Baker 1994; Caple et al. 2012a). A more detailed approach to performance testing can be accomplished with map creation from spatial data. Maps can be generated from georeferenced performance testing data to visually depict spatial variability of surface properties across a field. The introduction of spatial maps in turfgrass research over the last decade has brought forth the concept of precision turfgrass management (PTM) (Carrow et al. 2007, 2010; Bell and Xiong 2008; Stowell and Gelernter 2008; Krum et al. 2010; Straw et al. 2016, 2017a; Straw and Henry 2017). Precision turfgrass management is based on *site-specific* information, which allows managers to focus inputs where, when, and in the amount needed to potentially reduce expenditures and improve uniformity of turfgrass sites (Carrow et al., 2010). Performance testing can be thought of as the site assessment (i.e. data collection) component of PTM;

however, more intensive sampling is required in order to detect small-scale spatial variations (Straw et al. 2017a).

Previous performance testing studies (with and without spatial methods) have concluded that considerable spatiotemporal variations of surface properties exist (Holmes and Bell 1986; Baker and Isaac 1987; Baker and Gibbs 1989; Baker 1991; McClements and Baker 1994; Miller 2004; Freeland et al. 2008; Caple et al. 2012a, b; Straw et al. 2016, 2017a, b; Straw and Henry 2017). This may be attributed to environmental conditions, turfgrass species, soil texture, management practices, and the amount and location of field usage. Variations within and between fields can affect athlete perceptions of playing quality; consequently, standards for specific surface properties have been proposed to accommodate the athletes in certain sporting leagues (Canaway et al. 1990; McClements and Baker 1994; Aldous et al. 2005). Researchers have also discussed considering the within-field spatiotemporal variability of surface properties in future athlete injury studies due to its possible influence on injury risk (Stiles et al. 2009; Rennie et al. 2016).

Although the potential impact of spatiotemporal variability on playing quality and injury risk has been recognized, minimal management strategies focusing on improving field uniformity have been suggested. Precision turfgrass management may be a viable option, but constraints in current technology may make it difficult for turfgrass managers to efficiently obtain data of several surface properties. Furthermore, lack of understanding about the spatial relationships between surface properties over time, and on fields comprised of different soil textures, makes it difficult to know when to sample for map creation; particularly for sampling soil physical properties, which may be strongly influenced by soil moisture conditions at time of sampling (Straw et al. 2017a, b; Straw and Henry 2017). Therefore, the objective of this study was to utilize correlation coefficients and spatial maps to investigate the spatiotemporal relationship of several plant and soil properties on two natural turfgrass American football fields comprised of native and sand capped soils before and after irrigation. Results are used to identify key surface properties that may aid in efficient sampling for map creation and PTM implementation on turfgrass sports fields. The influence of irrigation is evaluated to determine if sampling at different soil moisture conditions effects spatial relationships and distributions.

Materials and methods

Field descriptions

Research was conducted on American football fields (48.8 m x 109.7 m) at Oconee County High School (OC) in Watkinsville, GA in September 2014 and at North Oconee High School (NO) in Bogart, GA in September and October 2015. These fields are playing surfaces for varsity, junior varsity, and freshman high school athletic games (football or soccer), as well as park and recreation youth sports activities. Oconee County and NO were each mowed at 2.5 cm and comprised of 'Tifway 419' hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) x *C. transvaalensis* Burtt-Davy] and 'Tifton 10' hybrid bermudagrass, respectively. Oconee County was constructed on native soil (79% sand, 8% silt, and 13% clay; sandy loam classification) and NO had a ~12.7 cm sand cap (92% sand, 2% silt, and 6% clay; sand classification) with clay beneath; neither site had subsurface drainage within the field.

In-ground irrigation systems were installed at both sites. The systems were comprised of I-25 rotary sprinklers with #8 nozzles (Hunter Industries Inc., San Marcos, California). Typical irrigation practices consisted of running irrigation zones for 30 and 24 minutes at OC and NO, respectively, at night (beginning ~12:00 AM) and as needed (generally 3-4 times per week during the growing season). The pressure of each system was ~483 kPa, which resulted in ~1 cm of water at OC, and ~0.8 cm of water at NO during an individual irrigation session.

Data collection

All data at each site were obtained using a georeferenced 4.8 m x 9.6 m sampling grid (120 samples). Soil moisture (volumetric water content; VWC), soil compaction (penetration resistance), turfgrass vigor (normalized difference vegetation index; NDVI), surface hardness, turfgrass shear strength, thatch depth, root biomass, and soil texture data were collected at each field. Volumetric water content, penetration resistance, NDVI, surface hardness, and turfgrass shear strength data were collected on three occasions (i.e. three replications) before (15 September, 22 September, and 27 September 2014 at OC and 16 September, 21 September, and 23 October 2015 at NO) and after (16 September, 23 September, and 28 September 2014 at OC and 17 September, 22 September, and 24 October 2015 at NO) irrigation during a dry period when the irrigation systems were the primary influence on soil moisture. Turfgrass shear strength data were measured only at NO due to sampling device availability. Sampling occurred ~12:00 PM on each date at both locations.

Volumetric water content, penetration resistance, and NDVI were simultaneously measured with the Toro Precision Sense 6000 (PS6000) (The Toro Company, Bloomington, Minnesota), a mobile multi-sensor device engineered for rapid sampling of turfgrass sites (Krum 2010; Straw et al. 2016, 2017a; Straw and Henry 2017). The sampling head on the PS6000 contained two stainless steel probes (9.5 mm diameter, 3.3 cm spacing, and 10 cm length) that were connected to a capacitance sensor (The Toro Company, Bloomington, Minnesota) and a load cell (Omega Engineering Inc., Stamford, Connecticut) that were used to measure VWC and penetration resistance, respectively, at a 0 to 10 cm depth. A GreenSeeker Model 500 active sensor (Trimble, Sunnyvale, California) mounted to the rear of the PS6000 measured NDVI of the turfgrass canopy. The sensor measured the reflectance of red (R = 660 nm ± 10 nm) and near-infrared (NIR = 770 nm ± 15 nm) spectra used to calculate the vegetation index ({NDVI = $[(R_{770} - R_{660})/(R_{770} + R_{660})]$}. A NovAtel Smart-AG™ GPS (NovAtel Inc., Alberta, Canada) with sub-meter real-time accuracy was attached to the PS6000 to gather latitudinal and longitudinal information for all data.

Surface hardness and turfgrass shear strength data were measured immediately following PS6000 sampling. Surface hardness was measured with a Clegg Impact Tester (Lafayette Instrument Co., Lafayette, Indiana). A 2.25 kg missile with an accelerometer at the end was dropped through a guide tube from a height of 0.45 m and measured attenuation upon impact with the surface (reported as Gmax; i.e. the ratio of peak deceleration on impact in gravities to the acceleration due to gravity). Turfgrass shear strength was measured with the Turf-Tec Shear Strength Tester (Turf-Tec Int., Tallahassee, Florida). A shear vane foot [twelve rectangular blades (six 19.1 mm length, 19.1 mm height, and 1.6 mm width and six 7.9 mm length, 19.1 mm height, and 1.6 mm width) fixed at 30° angles on a circular plate (7 cm diameter)] at the end of the device was inserted into the soil surface. A torque wrench handle was turned steadily and measured the highest amount of torque (Nm) until the turfgrass began to tear.

Soil cores were pulled on 16 September 2014 and 29 September 2015 at OC and NO, respectively, using polyvinyl chloride (PVC) pipe (5.1 cm diameter and 15.2 cm length) at each location of the georeferenced 4.8 x 9.6 m sampling grid to obtain thatch depth, root biomass, and soil texture (% sand, silt, and clay) data. Polyvinyl chloride pipes were completely inserted into the soil profile with a hand drilling hammer to ensure a core was pulled from a minimum depth of 12.7 cm. Thatch depth was measured by pushing upward on each soil core from the bottom of the PVC pipe with a wooden dowel (enough to expose approximately the top 5.1 cm of the core). Three thatch depth measurements (mm) were taken per soil core with a digital caliper and the average for each core was recorded. The leaf tissue above the soil was then removed with scissors and discarded.

Soil cores were pushed back into the PVC pipes until the cores were level with the top of the pipes. The PVC pipes were initially cut to a 12.7 cm length from the top with a table saw to assure consistent soil core volume (259.4 cm^3) between sample locations within the fields. Each 12.7 cm PVC pipe was cut 5.1 cm from the top with a table saw in order for root biomass to be measured at upper (0-5.1 cm) and lower (5.1-12.7 cm) depths. Soil cores were removed from the PVC pipes to air dry for ~1-3 d. The soil from both depths of a respective core was sieved (2 mm screen), combined, and kept to obtain texture data. Remaining rhizomes and soil were removed or washed to obtain root biomass at each depth of each soil core. Roots were oven dried at 50°C for 7 d prior to weighing for dry biomass (g). Particle size analysis for soil texture determination was completed using the hydrometer method (Bouyoucos 1962). Sodium hydroxide (NaOH) was added to aid soil dispersion [5:1, $(NaPO_3)_6$: NaOH].

Data analysis

Volumetric water content, penetration resistance, NDVI, surface hardness, and turfgrass shear strength data were averaged between the three replications at each location from the georeferenced 4.8 m x 9.6 m sampling grid before and after irrigation. The averaged data before and after irrigation were used for all analyses involving the aforementioned variables. First, descriptive statistics [minimum, maximum, range, mean, standard deviation, and coefficient of variability (CV)] were calculated to identify central tendencies, simple measures of variability, and dispersion of all data. Second, intercept only regression models were determined using the generalized least squares ('gls') function in the 'nlme' package of RStudio to evaluate if the temporal change in VWC, penetration resistance, NDVI, surface hardness, and turfgrass shear strength was significant before and after irrigation (RStudio team 2015; Pinheiro et al. 2016). Next, correlation coefficients were calculated using the 'modified.ttest' function in the SpatialPack package of RStudio to determine the strength and direction of relationship between all measured plant and soil properties (Clifford et al. 1989; Dutilleul 1993; Osorio and Vallejos 2014). Lastly, data were interpolated be means of ordinary kriging in ArcMap 10.3.1 (ESRI, Redlands, California) to generate spatial maps of all plant and soil properties at each site. Kriging uses a semivariogram (a graph with half the squared difference of the value between two points for all pairs of a dataset on the y axis, and the distance between two points for all pairs of a dataset on the x axis) to estimate spatial parameters (nugget, sill, and range) that are used in a set of linear equations that determine the best combinations of weights for data interpolation (Fortin and Dale 2005).

Results

Oconee County High School (native soil)

Mean VWC increased 20.9% ($\bar{x}$=19.6% to $\bar{x}$=23.7%), mean penetration resistance decreased 13.2% ($\bar{x}$=5.3 MPa to $\bar{x}$=4.6 MPa), mean NDVI remained the same ($\bar{x}$=0.74), and mean surface hardness decreased 13.9% ($\bar{x}$=66.4 Gmax to $\bar{x}$=57.2 Gmax) from before irrigation to after irrigation (Table 4.1). The difference of VWC (+4.4%; $P < 0.001$), penetration resistance (-0.67 MPa; $P < 0.05$), and surface hardness (-8.7 Gmax; $P < 0.001$) was significant, while the difference of NDVI was not (-0.003; $P = 0.209$). Only penetration resistance and surface hardness CV were noticeably influenced by irrigation (Table 4.1).

Volumetric water content, penetration resistance, NDVI, and surface hardness all had moderate to strong significant correlation coefficients with one another and the direction of their relationships did not change from before irrigation to after irrigation (Table 4.2). The moderate to high correlation coefficients led to comparable spatial distributions between each property (i.e. similar areas within the field of high or low values depending on direction of relationship) (Figure 4.1). For example, the north central area of the field appears to have the lowest VWC and NDVI values and the highest penetration resistance and surface hardness values. Even though the difference in magnitude of VWC, penetration resistance, and surface hardness was significant, the relationships and spatial distributions did not appear to change dramatically from before irrigation to after irrigation (Figure 4.1).

Volumetric water content and NDVI exhibited moderate to weak significant relationships with root biomass and soil texture, respectively (Table 4.2). Although negative relationships between VWC-total root biomass (before and after irrigation) and VWC-upper root biomass (after irrigation) were significant, their spatial distributions were contradictory (Figure 4.1). This was most evident in the northeast corner of the field, where VWC was lowest and root biomass appeared highest; however, in the center of the field, VWC was lowest and root biomass was lowest (Figure 4.1). The significant relationships between NDVI-sand content (before and after irrigation) and NDVI-silt content (before and after irrigation) did not result in similar spatial distributions (Table 4.2; Figure 4.1). The lowest NDVI, lowest silt content, and highest sand content of the north central area of the field may have contributed to the significance of these relationships (Figure 4.1).

Thatch depth was not significantly correlated with any of the measured properties; as a result, its spatial distribution was not comparable to others (Table 4.2; Figure 4.1). Root biomass and soil texture were self-correlated between depths and texture classifications, respectively; therefore, their correlation coefficients are not reported (Kenney 1982). The only significant relationships involving root biomass were total root biomass-VWC (before and after irrigation; previously mentioned), lower root biomass-VWC (after irrigation; previously mentioned), and lower root biomass-clay (Table 4.2). The lower root biomass-clay maps do not have similar spatial distributions, so their significant relationship is likely due to high lower root biomass and low clay content in the northeast corner of the field (Figure 4.1). The only significant relationships involving soil texture were sand-NDVI (before and after irrigation), silt-NDVI (before and after irrigation), and clay-lower root biomass (all previously mentioned) (Table 4.2).

North Oconee High School (sand capped)

Mean VWC increased 19.4% ($\bar{x}$=17.5% to $\bar{x}$=20.9%), mean penetration resistance decreased 9.3% ($\bar{x}$=5.4 MPa to $\bar{x}$=4.9 MPa), mean NDVI increased 4.9% ($\bar{x}$=0.58 to $\bar{x}$=0.61), mean surface hardness decreased 6.7% ($\bar{x}$=89.1 Gmax to $\bar{x}$=83.1 Gmax), and mean turfgrass shear strength remained the same ($\bar{x}$=14.9 Nm) from before irrigation to after irrigation (Table 4.3). The difference of VWC (+3.0%; $P < 0.001$), penetration resistance (-0.86 MPa; $P < 0.01$), and surface hardness (-6.0 Gmax; $P < 0.001$) was significant, while the difference of NDVI and shear strength was not [+0.02 ($P = 0.209$) and +0.02 Nm ($P = 0.928$), respectively]. Only the VWC CV, and to a lesser extent the penetration resistance CV, were noticeably influenced by irrigation (Table 4.3).

The relationships between VWC-NDVI, VWC-surface hardness, penetration resistance-NDVI, and NDVI-surface hardness resulted in minor changes from before irrigation to after irrigation, and in a couple instances even the significance level was altered (Table 4.4). Although a significant difference in VWC, penetration resistance, and surface hardness magnitude before and after irrigation was observed, their spatial distributions did not change dramatically (Figure 4.2). Similar conclusions can be made about the spatial distributions of NDVI and turfgrass shear strength (Figure 4.2).

Volumetric water content had significant relationships with several of the measured properties, including NDVI (before irrigation), surface hardness (before and after irrigation), turfgrass shear strength (before and after irrigation), total root biomass (before and after irrigation), and lower root biomass (before and after irrigation) (Table 4.4). The correlation coefficients were moderate between all relationships and only turfgrass shear strength, total root biomass, and lower root biomass appear to have similar large-scale spatial distributions as VWC, but several small-scale discrepancies can still be detected between maps (Table 4.4; Figure 4.2). The spatial distributions between VWC-NDVI and VWC-surface hardness are not comparable (Figure 4.2).

Penetration resistance and NDVI had a significant relationship with each other (before irrigation), as well as surface hardness (both before and after irrigation) and thatch depth (with penetration resistance after irrigation and with NDVI before and after irrigation) (Table 4.4). Penetration resistance, NDVI, and surface hardness maps are all comparable, particularly in the center of the field, where the highest penetration resistance and surface hardness values and lowest NDVI values were located (Figure 4.2). The thatch depth map was moderately comparable with penetration resistance and NDVI spatial distributions, especially down the center of the field (Figure 4.2). Thatch depth also had a significant relationship with surface hardness (before and after irrigation), which resulted in similar spatial distributions down the center of the field (Table 4.4; Figure 4.2).

Root biomass and soil texture were self-correlated between depths and texture classifications, respectively, so their correlation coefficients are not reported. Several significant relationships involving root biomass were observed with VWC, surface hardness, shear strength, and thatch depth (Table 4.4), but the most comparable maps were between total and lower root biomass, VWC, and turfgrass shear strength (previously mentioned) (Figure 4.2). The only significant relationship involving soil texture was clay-surface hardness (before irrigation), although their spatial distributions were not similar (Figure 4.2).

Discussion

Both study fields exhibited spatial variations of each measured field property. Previous work using spatial methods observed similar results on natural turfgrass sports fields. Miller (2004) and Freeland et al. (2008) reported spatial variation of surface hardness on two soccer fields (native soil and sand) and one American football field (sand). Carrow et al. (2010) detected spatial variability of VWC on two soccer fields (soil texture not mentioned). Caple et al. (2012b) mapped VWC, penetration resistance, surface hardness, and turfgrass shear strength on three soccer fields [clay loam, loamy sand, and sand (in top 5 cm) soil textures] and observed spatial variations for all properties. Straw et al. (2016; 2017a, b) and Straw and Henry (2017) concluded that spatial variability of VWC, penetration resistance, NDVI, and surface hardness existed on several fields of varying soil textures. To the authors' knowledge, this is the first study that attempted to evaluate the spatial variability of thatch depth, root biomass, and soil texture in natural turfgrass sports fields.

We observed minimal temporal differences in the strength of relationship between properties measured before and after irrigation, which resulted in minimal temporal differences of spatial distributions. Only the magnitude of measured properties was significantly affected by irrigation. This was the first study to evaluate differences from before irrigation to after irrigation, but similar short-term conclusions were drawn for VWC, penetration resistance, and NDVI during a 5 and 7 day irrigation dry down at OC and NO, respectively (Straw et al. 2017a), as well as an 8 day rainfall dry down at NO (Straw and Henry 2017). However, short-term temporal differences in spatial distributions of VWC, penetration resistance, and NDVI have been observed on a recreational sports field (native soil) during an 11 day rainfall dry down (Straw and Henry 2017). Temporal differences in spatial distributions of VWC and penetration resistance were also observed in a study on a recreational sports field (native soil) that compared maps generated from sampling after rainfall and irrigation, but in that same study surface hardness spatial distribution was not influenced by soil moisture condition (Straw et al. 2017b). These results suggest that sampling at different soil moisture conditions may or may not influence the spatial distributions of surface properties. For this reason, Straw et al. (2017a, b) suggests sampling *after* irrigation and rainfall (once the soil is at field capacity) in order to get a baseline of all interested properties under both soil moisture conditions. Then subsequent testing can be compared back to baseline data to determine whether improvements should be made or if management applications were effective.

A number of significant relationships between surface properties were observed on each field in this study, although significance did not always result in comparable spatial distributions between two properties. Typically, we observed that the stronger the correlation coefficient, the more similar the spatial distribution. It is challenging to compare these results to other studies since correlation coefficients and spatial maps have only been used twice (to date) to evaluate the spatiotemporal relationship between plant and soil properties in sports fields. In the study by Straw and Henry (2017), one of the two fields evaluated was NO, which produced similar results as our study. Results from the second field (native soil) evaluated by Straw and Henry (2017) were also agreeable; where strong significant relationships generally resulted in similar spatial distributions between measured properties, but spatial distributions between two properties were usually not comparable when significant relationships were weak to moderate. Straw et al. (2017b) did observe a moderate to strong significant relationship between VWC and penetration resistance [r = -0.66 ($P < 0.001$)] after irrigation, but their spatial distributions were not comparable; however, the study was non-replicated and took place on one field, making it difficult to draw strong conclusions. Caple et al. (2012b) calculated correlation coefficients, but did not present them in detail in order to make map comparisons.

Significant relationships on the native soil field were not always significant on the sand capped field. Too many contrasting relationships occurred between fields to discuss them all, so only a few relevant scenarios will be covered in detail in the subsequent discussion. Volumetric water content was highly correlated with penetration resistance and surface hardness on the native soil field, but those relationships were weaker on the sand capped field. Negative relationships between soil moisture and soil physical properties have been recognized in several other non-spatial studies where data were pooled across several fields (Bell and Holmes, 1988; Rogers et al., 1988; Holmes and Bell, 1986; McClements and Baker, 1994). Caple et al. (2012a) evaluated relationships on individual fields and observed a dramatic decrease in relationship strength between penetration resistance and soil water content on a sand field (r = -0.15), compared to a sandy loam/sandy clay loam field [r = -0.95 ($P < 0.05$)], two loamy sand/clay loam fields [r = -0.92 ($P < 0.05$) and -0.94 ($P < 0.05$)], a clay field [r = -0.82 ($P < 0.05$)], and another sand field [r = - 0.75 ($P < 0.05$)]. The sand fields had different types of reinforcement materials, which resulted in varying ranges of soil water content throughout the season (Caple et al., 2012a). The differences in the strength of relationships between fields comprised of native and sand soils suggests that pooling data across fields of different soil textures can obscure the assessment of site-specific relationships.

Strong relationships between VWC, penetration resistance, and surface hardness on the native soil field resulted in comparable spatial distributions. Native soils are more susceptible to increased levels of soil compaction and decreased amounts of water infiltration (compared to sand soils) due to the presence of finer soil particles (Beard 1972). Concentrated areas of high penetration resistance (i.e. soil compaction) in the north central area at OC were likely caused by excessive foot traffic from gameplay and may have contributed to reduced water infiltration and a harder surface. Penetration resistance and surface hardness on the sand capped field did not appear to influence water infiltration; therefore, the spatial distribution of VWC was possibly related to the slope of the underlying clay layer.

Normalized difference vegetation index on the native soil field had moderate to strong relationships and similar spatial distributions with VWC, penetration resistance, and surface hardness. Relationships were much weaker and not always significant on the sand capped field, which only resulted in NDVI-penetration resistance and NDVI-surface hardness having comparable spatial distributions. Normalized difference vegetation index data have been utilized in turfgrass research to indicate color, chlorophyll content, shoot density, and shoot injury of a canopy (Trenholm et al. 1999; Bell et al. 2002; Bremer et al. 2011). The relationship between NDVI and soil moisture has also been investigated to determine whether NDVI is an accurate indicator of turfgrass drought stress (Jiang et al. 2009; Johnsen et al. 2009; Krum et al. 2010; McCall et al. 2017). Relationship strength between NDVI and soil moisture has varied between studies ($r = 0.22$-0.71) and factors other than soil moisture stress were reported to affect NDVI readings. Our results suggest that NDVI may be useful to identify wear and/or soil compaction stress (from foot traffic) on sports fields constructed with native or sand capped soils, but it was only capable of identifying low VWC areas on the native soil field. However, it is difficult to differentiate the causality of low NDVI from various types of potential stresses (such as water, soil compaction, or wear stress).

Thatch depth was not significant with any property on the native soil field, but with several properties on the sand capped field. Significant relationships between thatch depth and penetration resistance, NDVI, surface hardness, and root biomass occurred on the sand capped field. These relationships were weak, but did lead to comparable large-scale spatial distributions. Interestingly, thatch depth was not significantly related to turfgrass shear strength. The presence of thatch has been thought to result in higher shoe-surface friction, which may lead to a potentially higher risk for lower extremity athlete injuries (McNitt et al. 1997; Orchard et al. 2005, 2013). Unfortunately, turfgrass shear strength was not measured on the native soil field. It was more related to soil moisture and root biomass (total and upper depth) on the sand capped field and was most comparable to the spatial distribution of VWC. These significant relationships may be attributed to deeper insertion of the shear vane into the soil profile when VWC was higher, as well as increased root biomass providing rotational resistance when turning the torque wrench handle.

No significant relationship between root biomass (at any depth) and penetration resistance was observed, and spatial distributions of these properties were not comparable on either field. Negative root response due to soil compaction is cause by reduced aeration and altered soil water status from the compression of soil particles (i.e. fewer macropores) (Carrow and Petrovic 1992). The level of soil compaction may not have been high enough on either field to significantly alter root growth, which may have led to this result.

Conclusions

This study evaluated the spatiotemporal relationship of several plant and soil properties in order to identify key properties that may aid in efficient sampling for map creation and PTM implementation on sports fields. The spatial distribution of root biomass and soil texture had minimal influence on the spatial distribution of all other measured surface properties. Soil moisture had the strongest influence and the most similar spatial distribution with other properties on the native soil field; therefore, it may be used as a guide to predict the spatial distribution of other field properties. For example, VWC may be used to assess penetration resistance, NDVI, and surface hardness levels due to the significant relationships and similar spatial distributions we observed. Maps of VWC following irrigation may be utilized to identify malfunctioning irrigation heads within a field (Carrow et al., 2010; Straw et al. 2017b; Straw and Henry, 2017). Volumetric water content maps could also be used to identify areas for site-specific cultivation in order to reduce soil compaction and hardness levels, improve water infiltration, and increase turfgrass vigor (Carrow et al., 2010; Straw et al. 2017b; Straw and Henry, 2017).

Soil moisture was not as influential on the sand capped field and only had a strongly comparable spatial distribution with turfgrass shear strength. It would be difficult to utilize the VWC maps for the identification of irrigation system deficiencies due to water movement beneath the surface. Although VWC and turfgrass shear strength spatial distribution may improve through the minimization of sub-surface water movement, it would be difficult to do without complete field reconstruction. The only other strong to moderate relationship observed on this field was between penetration resistance and surface hardness. The spatial distribution of NDVI, penetration resistance, and surface hardness was comparable on both study fields, which suggests that measuring only one of these properties may be necessary regardless of soil type. The weak to moderate relationships between these properties on both fields (particularly the sand capped field) do warrant further investigation.

The implementation of PTM requires the creation of management zones (e.g. site-specific management units; SSMUs) that aid in the identification of areas that are in need of attention (Carrow et al. 2010; Krum et al. 2010; Straw and Henry 2017). Understanding the spatiotemporal relationships of plant and soil properties could also improve performance testing strategies using SSMUs. For example, identifying SSMUs of low VWC may also indicate areas of high surface hardness on native soil fields. Subsampling and monitoring surface hardness levels within low VWC SSMUs may be more efficient than sampling and creating a map of surface hardness. If surface hardness values exceed a certain threshold then site-specific irrigation could potentially be implemented to reduce surface hardness levels and improve uniformity prior to play (Straw and Henry 2017). Similar strategies could be implemented to improve turfgrass shear strength uniformity on sand capped fields; however, the fact that most irrigation systems have zones which aren’t single head controlled may be a limiting factor.

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Table 4.1 Descriptive statistics of volumetric water content (VWC), penetration resistance, normalized difference vegetation index (NDVI), and surface hardness before and after irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at Oconee County High School (native soil).

	Min	Max	Range	Mean	SD	CV (%)
			%			
VWC (before)	6.21	31.39	25.18	19.59	4.99	25.47
VWC (after)	9.33	37.97	28.64	23.70	6.07	25.61
			MPa			
Penetration resistance (before)	2.76	9.05	6.29	5.31	1.36	25.61
Penetration resistance (after)	2.07	10.47	8.40	4.62	1.59	34.42
NDVI (before)	0.40	0.82	0.42	0.74	0.07	9.46
NDVI (after)	0.47	0.82	0.35	0.74	0.06	8.11
			Gmax			
Surface hardness (before)	41.67	95.67	54.00	66.44	10.07	15.16
Surface hardness (after)	34.67	82.67	48.00	57.17	11.58	20.26
			mm			
Thatch depth	5.80	30.40	24.6	13.31	4.84	36.36
			g			
Root biomass (total)	0.14	1.45	1.31	0.49	0.20	40.82
Root biomass (upper)	0.08	0.69	0.61	0.28	0.10	35.71
Root biomass (lower)	0.04	1.08	1.04	0.21	0.14	66.67
			%			
Sand	67.60	93.20	25.60	78.94	4.64	5.88
Silt	2.20	14.40	12.20	8.36	2.90	34.69
Clay	4.60	23.60	19.00	12.70	3.07	24.17

Table 4.2 Correlation coefficient matrix showing the relationship between volumetric water content (VWC), penetration resistance, normalized difference vegetation index (NDVI), and surface hardness before and after (in parentheses) irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at Oconee County High School (native soil).

	VWC	**Penetration resistance**	**NDVI**	**Surface hardness**	**Thatch depth**	**Root biomass (total)**	**Root biomass (upper)**	**Root biomass (lower)**	**Sand**	**Silt**	**Clay**
VWC	1	-0.66*** (-0.71***)	0.57** (0.62**)	-0.80*** (-0.89***)	-0.07 (-0.08)	-0.23* (-0.22*)	-0.26 (-0.28*)	-0.03 (-0.07)	-0.07 (-0.02)	0.08 (0.07)	0.02 (-0.03)
Penetration resistance		1	-0.57* (-0.60**)	0.77*** (0.80***)	0.04 (0.08)	0.18 (0.10)	0.22 (0.20)	0.05 (-0.03)	0.00 (-0.04)	-0.13 (-0.04)	0.13 (0.07)
NDVI			1	-0.68* (-0.68**)	0.04 (0.03)	0.00 (-0.08)	-0.10 (-0.17)	0.10 (0.04)	-0.29* (-0.34*)	0.31** (0.33**)	0.15 (0.20)
Surface hardness				1	0.07 (0.14)	0.14 (0.16)	-0.08 (-0.02)	0.02 (0.06)	0.08 (0.05)	-0.18 (-0.14)	0.05 (0.06)
Thatch depth					1	0.06	0.12	0.02	-0.19	0.07	0.18
Root biomass (total)						1	-	-	0.12	-0.03	-0.16
Root biomass (upper)							1	-	-0.01	0.07	-0.04
Root biomass (lower)								1	0.18	-0.07	-0.20*
Sand									1	-	-
Silt										1	-
Clay											1

*,**,*** significant at the 0.05, 0.01, 0.001 probability level, respectively.

Table 4.3 Descriptive statistics of volumetric water content (VWC), penetration resistance, normalized difference vegetation index (NDVI), surface hardness, and shear strength before and after irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at North Oconee High School (sand capped).

	Min	Max	Range	Mean	SD	CV (%)
			%			
VWC (before)	6.36	27.59	21.23	17.48	4.86	27.80
VWC (after)	9.25	30.64	21.39	20.89	4.15	19.87
			MPa			
Penetration resistance (before)	3.41	8.57	5.16	5.44	1.01	18.57
Penetration resistance (after)	3.01	7.94	4.93	4.90	1.10	22.45
NDVI (before)	0.32	0.71	0.39	0.58	0.06	10.34
NDVI (after)	0.36	0.72	0.36	0.61	0.06	9.84
			Gmax			
Surface hardness (before)	71.33	115.67	44.34	89.11	8.50	9.54
Surface hardness (after)	67.33	108.33	41.00	83.13	8.02	9.65
			Nm			
Shear strength (before)	9.83	20.17	10.34	14.90	2.30	15.44
Shear strength (after)	9.33	20.50	11.17	14.92	2.50	16.76
			mm			
Thatch depth	7.50	17.20	9.70	11.64	2.21	18.99
			g			
Root biomass (total)	0.06	0.54	0.48	0.25	0.09	36.00
Root biomass (upper)	0.01	0.30	0.29	0.11	0.05	45.45
Root biomass (lower)	0.03	0.33	0.30	0.14	0.05	35.71
			%			
Sand	82.00	96.20	14.20	92.04	2.09	2.27
Silt	0.60	4.60	4.00	2.06	0.92	44.66
Clay	2.40	14.80	12.40	5.90	1.59	26.95

Table 4.4 Correlation coefficient matrix showing the relationship between volumetric water content (VWC), penetration resistance, normalized difference vegetation index (NDVI), surface hardness, and shear strength before and after (in parentheses) irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at North Oconee High School (sand capped).

	VWC	**Penetration resistance**	**NDVI**	**Surface hardness**	**Shear strength**	**Thatch depth**	**Root biomass (total)**	**Root biomass (upper)**	**Root biomass (lower)**	**Sand**	**Silt**	**Clay**
VWC	1	-0.29 (-0.04)	0.41* (0.24)	-0.48* (-0.44*)	0.58*** (0.59***)	0.24 (0.16)	0.35* (0.35*)	0.24 (0.24)	0.34* (0.34*)	0.09 (0.09)	-0.06 (-0.11)	-0.06 (-0.02)
Penetration resistance		1	-0.37* (-0.28)	0.66*** (0.65**)	0.01 (0.01)	-0.20 (-0.32**)	-0.18 (-0.12)	-0.11 (-0.04)	-0.18 (-0.15)	0.04 (0.13)	-0.01 (-0.18)	-0.06 (-0.03)
NDVI			1	-0.47* (-0.37*)	0.15 (0.19)	0.25* (0.21*)	0.23 (0.19)	0.19 (0.18)	0.21 (0.14)	0.06 (0.11)	-0.02 (0.02)	-0.10 (-0.20)
Surface hardness				1	-0.10 (-0.28)	-0.29* (-0.24*)	-0.31* (-0.28)	-0.29* (-0.15)	-0.23 (-0.31*)	0.22 (0.18)	-0.12 (-0.09)	-0.20* (-0.18)
Shear strength					1	0.14 (0.05)	0.29* (0.32*)	0.26* (0.32*)	0.24* (0.23)	0.18 (0.13)	-0.14 (-0.06)	-0.14 (-0.15)
Thatch depth						1	0.23*	0.21*	0.17	-0.02	0.09	-0.04
Root biomass (total)							1	-	-	0.16	-0.17	-0.14
Root biomass (upper)								1	-	0.14	-0.17	-0.10
Root biomass (lower)									1	0.14	-0.13	-0.13
Sand										1	-	-
Silt											1	-
Clay												1

*,**,*** significant at the 0.05, 0.01, 0.001 probability level, respectively.

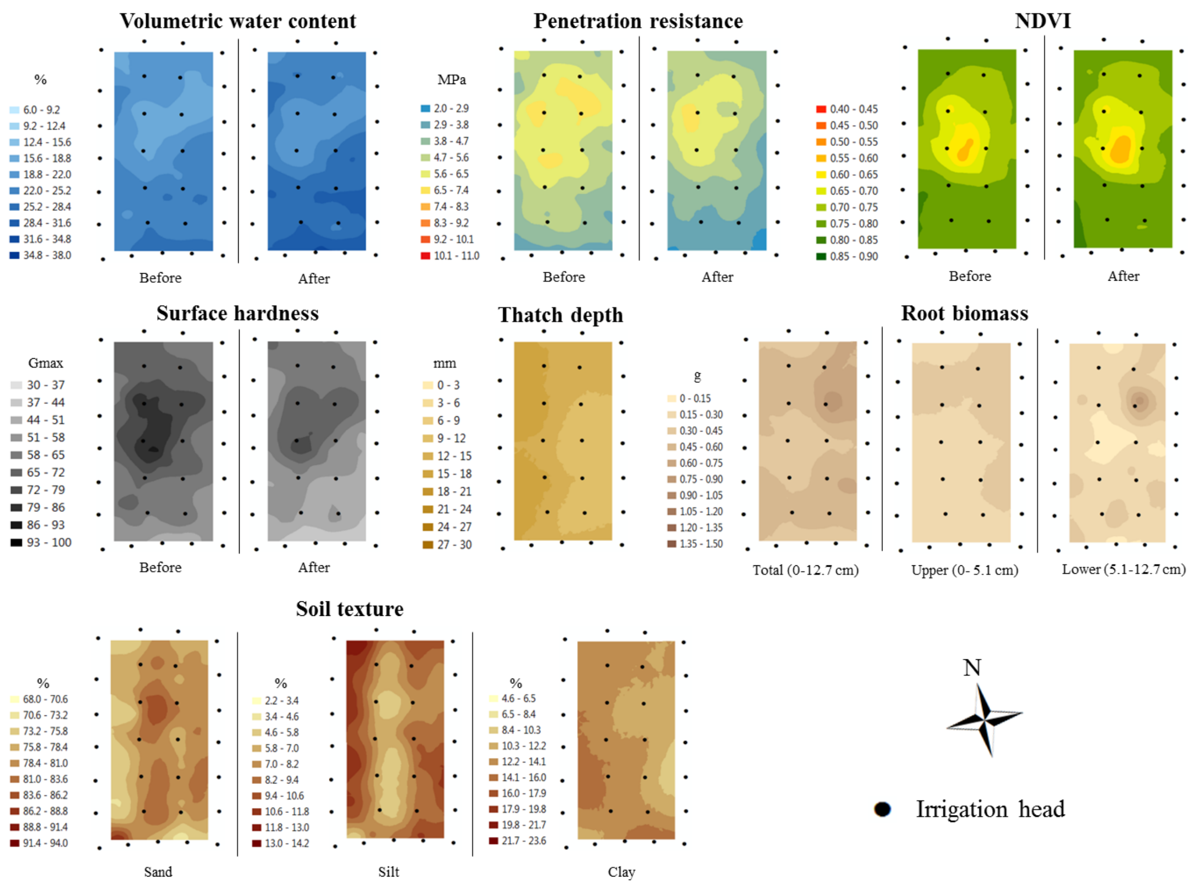

Figure 4.1 Spatial maps of volumetric water content, penetration resistance, normalized difference vegetation index (NDVI), and surface hardness before and after irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at Oconee County High School (native soil). Black dots are irrigation heads.

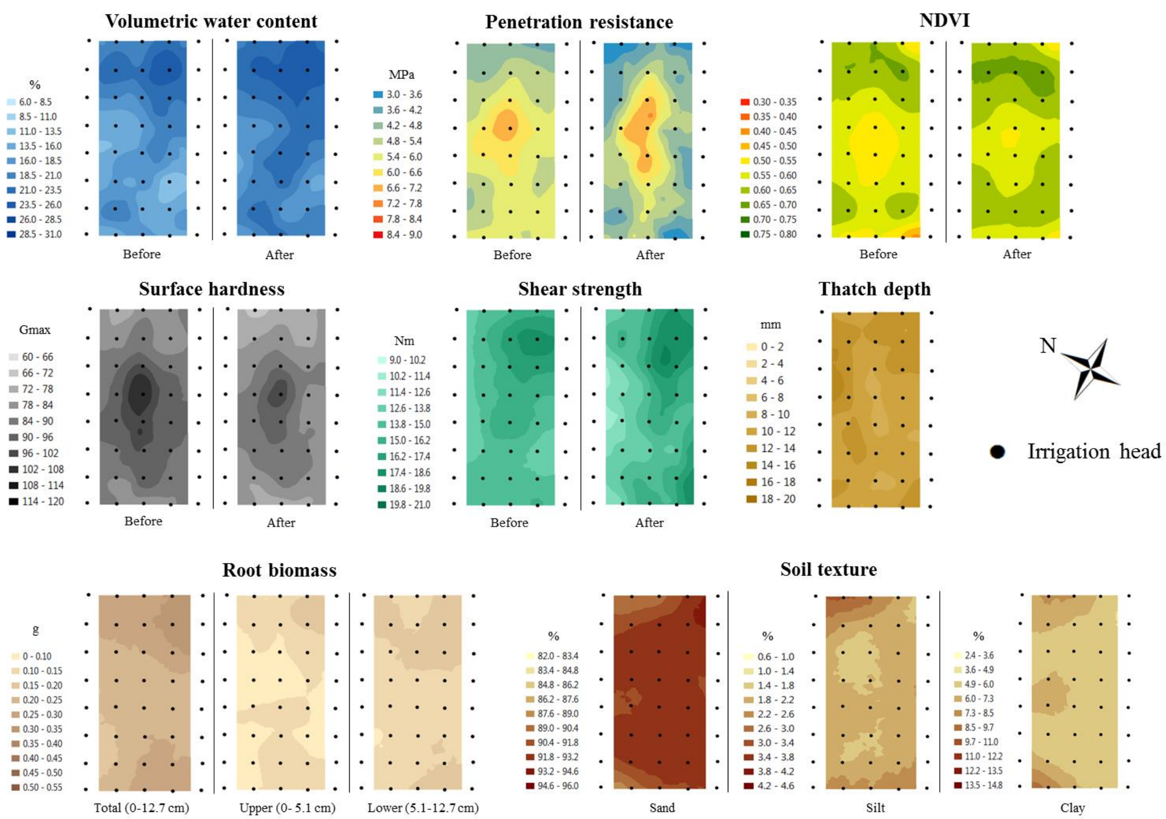

Figure 4.2 Spatial maps of volumetric water content, penetration resistance, normalized difference vegetation index (NDVI), surface hardness, and turfgrass shear strength before and after irrigation, as well as thatch depth, root biomass [total (0-12.7 cm), upper (0-5.1 cm), and lower (5.1-12.7 cm) depths], and soil texture (sand, silt, and clay) at North Oconee High School (sand capped). Black dots are irrigation heads.

CHAPTER 5

SPATIOTEMPORAL VARIATION OF SITE-SPECIFIC MANAGEMENT UNITS ON NATURAL TURFGRASS SPORTS FIELDS DURING DRY DOWN[1]

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Abstract

Site-specific management units (SSMUs) are fundamental for the implementation of Precision Turfgrass Management. Short-term spatiotemporal variations of soil compaction and turfgrass vigor may be dynamic during a dry down period on natural turfgrass sports fields. This is due to the inverse relationship between soil compaction and soil moisture/drought stress, which may impact SSMU delineation and identification of site-specific deficient areas within a field. The spatiotemporal change of soil moisture, soil compaction, and turfgrass vigor SSMUs [as measured by volumetric water content (VWC), penetration resistance, and normalized difference vegetative index (NDVI)] were evaluated three times during a dry down from rainfall on native soil and sand capped natural turfgrass sports fields. The relationship of penetration resistance and NDVI with VWC was strongest and only significant on the native soil field during the dry down period. In general, as the fields dried, the magnitude of VWC SSMUs and NDVI SSMUs decreased, while the magnitude of penetration resistance SSMUs increased. This phenomenon was more drastic on the native soil field. Significant changes in spatial distributions were observed for VWC SSMUs and penetration resistance SSMUs on the native soil field; however, minimal changes were reported on the sand capped field. The spatial distributions of NDVI SSMUs were minimal on both fields. It is concluded that short-term spatiotemporal variations of SSMUs on sports fields during a dry down can be significant and considerations should be made prior to sampling based on the objective.

Introduction

Soil compaction and wear from foot traffic are the major stresses that are imposed on natural turfgrass sports fields during game play (Carrow and Petrovic 1992). Soil compaction often causes a decline in turfgrass growth, quality, and persistence by negatively impacting soil aeration, soil strength, or plant and soil moisture relationships (Rosenberg 1964: Grable 1966; Barley and Greacen 1967; Madison 1971). Wear may inflict pressure, scuffing, or tearing of the plant tissue, causing a decrease in turfgrass health and vigor (Carrow and Petrovic 1992). The combined effect of these stresses can also influence other sports field properties (e.g. surface hardness and ground cover) associated with player safety (i.e. player-surface interactions) and field playability (i.e. ball-surface interactions) (Bell et al. 1985; Holmes and Bell 1986; Baker and Canaway 1993).

A combined approach of several cultural practices, such as irrigation, aerification, and fertilization, are often conducted by sports field managers to mitigate stresses from foot traffic. Typically, these cultural practices are applied homogeneously; however, within-field variability of soil compaction and turfgrass vigor can be dynamic due to interactions between field use, field management, climate, plant, and soil factors (Freeland et al. 2008; Carrow et al. 2010; Flitcroft et al. 2010; Caple et al. 2012; Straw et al. 2016). Therefore, scheduled applications of cultural practices made to an entire field or sports complex may be unnecessary and lead to misappropriation of management inputs.

Precision Turfgrass Management (PTM) has recently been adopted to increase input efficiency on turfgrass sites (Bell and Xiong 2008; Stowell and Gelernter 2008 Carrow et al. 2010; Krum et al. 2010). PTM requires detailed site information obtained through intensive data sampling in order to implement site-specific application of management inputs focused on areas of need. Previous turfgrass studies have utilized geographic information system technology to generate spatial maps from geo-referenced field data for the detection of deficient locations (Miller 2004; Freeland et al. 2008; Flitcroft et al. 2010; Krum et al. 2010; Caple et al. 2012; Straw et al. 2016). Spatial maps assist in the delineation of site-specific management units (SSMUs), or management zones, that have similar plant and soil characteristics (Carrow et al. 2010; Krum et al. 2010; Flitcroft et al. 2010). Management inputs can be focused on individual SSMUs to improve uniformity of the turfgrass site.

Extensive research has been conducted on SSMUs in precision agriculture (a parallel to PTM for agriculture) (Boydell and McBratney 2002; Corwin and Lesch 2005; Duffera et al. 2007; Yan et al. 2007; Corwin and Lesch 2010; López-Lozano et al. 2010; Davatgar et al. 2012); however, adoption has been slow in turfgrass for several reasons outlined by Carrow et al. (2010). Currently, only two studies have been published involving the use of SSMUs in turfgrass (both on golf course fairways). Krum et al. (2010) developed a protocol to delineate soil moisture (volumetric water content; VWC) SSMUs based on field capacity VWC (after rainfall) maps, and secondary considerations of turfgrass vigor (normalized difference vegetative index; NDVI) and elevation maps, for site-specific irrigation. Flitcroft et al. (2010) mapped VWC and soil compaction (penetration resistance), at field capacity (after rainfall) and under drier conditions (solely irrigation), to define SSMUs for site-specific aerification.

In addition to increased input efficiency, SSMUs of natural turfgrass sports fields may improve performance testing. Quantification of sports field properties through performance testing to determine field safety and playability has garnered more attention in recent years (McAuliffe 2008; Carrow et al. 2010; Aldahir and McElroy 2014). Sampling for performance testing differs from PTM. Performance testing protocols require sampling at 5-12 locations across a field, with conclusions based on the average (Holmes and Bell 1986; Canaway et al. 1990; McClements and Baker 1994; Jennings-Temple et al. 2006; Bartlett et al. 2009). Recent research has utilized more intense sampling and spatial maps to document significant variability in soil compaction and turfgrass vigor within sports fields (Caple et al. 2012; Straw et al. 2016). Results from these studies indicate that current and previous performance testing methodology ignores field variability and encourages homogeneous management.

Furthermore, short-term temporal variations during a dry down (from rainfall or routine irrigation) may occur with respect to soil compaction and turfgrass vigor due to the inverse relationship of soil physical properties with soil moisture and drought stress, respectively (Henderson et al. 1988; Carrow 1996). Short-term spatiotemporal variations may have implications on SSMUs to properly identify deficient areas. Therefore, the primary objective of this study was to evaluate the spatiotemporal change of soil moisture, soil compaction, and turfgrass vigor SSMUs [as measured by VWC (%), penetration resistance (MPa), and NDVI, respectively] during a dry down from rainfall on native soil and sand capped natural turfgrass sports fields. The goal is to provide an understanding of the spatiotemporal relationship between the properties, which may lead to improved sampling techniques using SSMUs on natural turfgrass sports fields.

Materials and methods

Field descriptions

Research was conducted at Oconee Veterans Park (Oconee Park; Watkinsville, GA) and North Oconee High School (North Oconee; Bogart, GA) in September 2014 and October 2015, respectively. Oconee Park is a recreational sports field (61.0 m wide and 97.5 m long) comprised of ‘TifSport’ hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) x *C. transvaalensis* Burtt-

Davy]. This field is primarily used for youth soccer, but is also open to the public for non-sporting events. Prior to data collection at Oconee Park two small soccer fields were positioned parallel to one another within the northern and southern portions of the field and extended from side to side. North Oconee is a football field (48.8 m wide and 109.7 m long) comprised of 'Tifton 10' hybrid bermudagrass. It hosts freshmen, junior varsity, and varsity high school football games, as well as youth football games. A composite sample of 16 soil cores (approximately 13 mm in diameter pulled to a 100 mm depth) obtained across each field were used for texture analysis. Oconee Park was constructed on a native sandy loam soil (70% sand, 14% silt, and 16% clay) and North Oconee had a 127 mm sand cap (94% sand, 4% silt, and 2% clay) above a clay sublayer. Neither site had subsurface drainage.

Data collection

VWC, penetration resistance, and NDVI were simultaneously measured with the Toro Precision Sense 6000 (PS6000) mobile sampling device (The Toro Company, Bloomington, MN). The PS6000 was towed behind a utility vehicle and traversed each field at a speed of 2.7 to 3.3 km h^{-1} (Krum et al., 2010). Measurements were recorded approximately every 2.4 m and passes downfield were 4.8 m apart; therefore, a 2.4 x 4.8 m sampling grid was utilized (~530 and ~450 samples at Oconee Park and North Oconee, respectively).

VWC data were measured by a capacitance sensor (The Toro Company, Bloomington, MN) to obtain soil moisture at a 0-100 mm depth. To ensure the depth, two stainless steel probes (9.5 mm diameter, 33 mm spacing, and 100 mm length) were installed on a sensor mounted on the end of an arm attached to one end of a shaft. The wheel-driven shaft rotates when the PS6000 unit moves forward resulting in a circular motion of the arm. The sensors probes enter the soil as the arm moves and a plate passes a proximity switch that triggers the data loggers to take a measurement. A clutch switch on the user interface display controls this process. The clutch switch is activated once the PS6000 makes a pass within the test area and is deactivated between turns outside the test area. Once the clutch is activated, continuous measurements are made without stopping the PS6000. The capacitance sensor was calibrated in a lab by the manufacturer using three different soil types at various levels of moisture. The "actual" moisture content for each soil was determined by weighing the sample when wet, then again after drying to measure the difference. A calculated best fit equation from all the soils in the lab was then used to determine VWC with the PS6000 in the field.

Penetration resistance data were measured with a 19 mm diameter stainless steel compression load cell (Omega Engineering Inc., Stamford, CT) located in the soil sampling head of the PS6000. The sensor measures the maximum penetration force transferred to the load cell (top 100 mm of the soil profile) from two probes and is recorded as pounds of force (converted to MPa). The same probes and methodology used to collect VWC were used to acquire penetration resistance data.

NDVI data were collected using a GreenSeeker Model 500 active sensor (Trimble, Sunnyvale, CA) mounted to the PS6000. NDVI sensors have internal light emitting diodes and a photodiode optical detector that measured the reflectance centered at red (R = 660 nm ± 10 nm) and near-infrared (NIR = 770 nm ± 15 nm) spectra. The sensors internal light source reduces the influence of solar radiation on the measurements. A vegetative index ($\{NDVI = [(R_{770} - R_{660})/(R_{770} + R_{660})]\}$) was calculated (0 to1, where 1 is best) from the reflectance readings. NDVI provides an indication of color, percent live cover, shoot density, and shoot injury of the turfgrass canopy (Trenholm et al. 1999; Bell et al. 2002; Bremer et al. 2011). Although it was recently reported that cloud cover has minimal effect on NDVI (Zhang et al. 2015), data collection each day at both fields took place under minimal cloud conditions (specific weather data are not reported). Additionally, a NovAtel Smart-AG™ GPS (NovAtel Inc., Alberta, Canada) with sub-meter real-time accuracy was attached to the PS6000, which gathered latitudinal and longitudinal information for all data.

VWC, penetration resistance, and NDVI were measured 3 times at each field during a dry down from rainfall. Approximately 15 mm of rain occurred on 7 September 2014 at Oconee Park, the day prior to initial data collection. Data were collected with the PS6000 on 8 September (day 1 of dry down), 11 September (day 4 of dry down), and 18 September (day 11 of dry down) 2014. Dry down took place during a time when irrigation to the field was limited (the parks irrigation ponds were low). The field is typically irrigated 2-3 times a week; therefore, day 11 of dry down represents an extreme case of soil dryness. Visible drought symptoms were becoming apparent by day 11 of the dry down, which forced the turf manager to irrigate following our data collection that day.

At North Oconee, approximately 46 mm of rain occurred on 10 October 2015 and another 5 mm on 13 October 2015. Heavy rainfall at North Oconee caused puddling due to the presence of clay beneath the 127 mm sand cap, so data collection was not initiated until excess water had drained. Once the field was at or just beneath field capacity, data were collected with the PS6000 on 16 October (day 1 of dry down), 20 October (day 5 of dry down), and 23 October (day 8 of dry down) 2015. Dry down at North Oconee took place for only 8 days, because it was the longest amount of time that the turfgrass manager would allow. No clear symptoms of drought stress were apparent by day 8 of the dry down.

Data analysis

Descriptive statistics [minimum, maximum, range, mean, standard deviation (SD), and coefficient of variability (CV)] were calculated in RStudio for VWC, penetration resistance, and NDVI during each day of dry down at Oconee Park and North Oconee (RStudio team 2015). Correlation coefficients were calculated using the ‘modified.ttest’ function in the SpatialPack package of RStudio to determine the strength and direction of relationship between each property on each day (Osorio and Vallejos 2014). This function takes into account the spatial association between each property in order to calculate a corrected Pearson’s r correlation coefficient (Clifford et al. 1989; Dutilleul 1993). Penetration resistance data at Oconee Park on day 4 and 11 were negatively skewed. It is recommended to calculate Spearman’s ρ instead of Pearson’s r for skewed data (Zou et al. 2003); however, the Spearman correlation is essentially the Pearson correlation calculated from the ranks of the data. Therefore, modified t-tests between penetration resistance and VWC, and penetration resistance and NDVI, at Oconee Park on day 4 and day 11 were conducted on the ranks of each dataset to adjust for skewness. The correlation coefficients are between -1 and 1. A negative value indicates a negative relationship (i.e. as one property increases the other decreases) and a positive value indicates a positive relationship (i.e. as one property increases the other also increases). The closer the coefficient is to -1 or 1, the stronger the negative or positive relationship, respectively.

Spatial maps were used to visually compare the variability of each field property during dry downs. The maps were generated in the geospatial processing program ArcMap 10.3.1 (ESRI, Redlands, CA) by first plotting the empirical semivariograms. A semivariogram has half the squared difference of the value between two points for all pairs of a dataset on the y axis, and the distance between two points for all pairs on the x axis. The number of bins was calculated from half the maximum distance in the data set divided by the respective sampling grid spacing (Schabenberger and Gotway 2005). Bins are a method to departmentalize lags (i.e. the distance and direction between two data points) that have similar distance and direction (Johnston et al. 2001). The lag size was the average of the sampling grid used [(2.4 + 4.8)/2 = 3.6] (Johnston et al. 2001). The exponential, spherical, or gaussian models were evaluated and the model with the best visual fit was selected. The model with the lowest root-mean-square error was chosen when multiple models fit similarly. The gaussian model is generally seen as an "artificial" model for spatial dependence and does not command respect among alternatives (Schabenberger and Gotway 2005); therefore, the gaussian model was not given consideration when exponential or spherical models fit comparably. The nugget (the point that intercepts the y axis and is measurement error, variations at small spatial scales, or both), range (separation distances between two points less than the range are spatially autocorrelated and separation distances above the range are not), and sill (the semivariance at the range) parameters describe the spatial structure of the semivariogram (Johnston et al. 2001). No anisotropy was evident from the semivariograms.

Once the semivariogram models were chosen ordinary kriging was used to estimate the values for points on the field that were not sampled. The equation for the ordinary kriging predictor is:

$$\hat{\mathrm{Z}}(\mathrm{s}_0) = \hat{\mu} + \boldsymbol{\sigma}'\boldsymbol{\Sigma}^{-1}(\mathbf{Z}(s) - \mathbf{1}\hat{\mu}) \quad (1)$$

where s_0 in an unmeasured location, $\hat{Z}(s_0)$ is the unknown value at the location s_0, $\hat{\mu}$ is the generalized least squares estimator of the average value, $\boldsymbol{\sigma}$ = cov[$\mathbf{Z}$(s), Z(s_0)] {n x 1 vector of covariances between the values Z(s_i) [where i = 1 to n (number of measured points)] and Z(s_0); cov[Z(s_i), Z(s_0)] is a function of the semivariogram and therefore based on the distance between

s_i and s_0 for each i}, $\mathbf{\Sigma}$ = var[$\mathbf{Z}$(s)] {n x n matrix with C(0) on the diagonal [variances of $Z(s_i)$ for each i] and cov[$Z(s_i)$, $Z(s_j)$], i, j = 1 to n, $i \neq j$ in the off-diagonal entries}, and $\mathbf{Z}(\mathbf{s})$ is a vector of known values of measured locations. Data does not need to be normally distributed when using kriging as a predictor (Johnston et al. 2001); therefore, penetration resistance data at Oconee Park on day 4 and day 11 were not transformed prior to kriging. Maps are presented with equal interval legend classifications based on the overall range of each field property on all days of dry down.

Delineation of SSMUs was done following a protocol by Krum et al. (2010). They primarily used histogram- and SD-based maps to determine SSMU boundaries of VWC on two golf course fairways. The histogram-based map legends were chosen based on estimated similar soil types from the VWC histograms. We felt it was unnecessary to use histogram-based maps in our study, because sports fields are typically smaller and flat compared to a golf course fairway, and in several instances constructed on man-made soils (e.g. North Oconee); therefore, significant variations in soil type are not likely.

The SD-based map legends were calculated by centering the SD around the mean, then the SD was added or subtracted to create the 2 upper and lower intervals, respectively. An advantage of defining map intervals by SD is that it clearly presents the highest and lowest classes, which are of the most interest for management decisions (Krum et al. 2010). Our SD intervals generally resulted in 5 classifications (with exception of penetration resistance on day 4 and day 11 at Oconee Park, which had 4). The SD-based maps were used as a guide to determine SSMU boundaries with the “create feature” tool in ArcMap.

It is of practical importance to determine the fewest amounts of SSMUs within each field (Krum et al. 2010); therefore, we classified our SSMUs into low, moderate, and high using the

SD-based legend classifications. High and low SSMUs were typically > plus or minus 0.5 SD from the mean, respectively. There were instances where small areas of difference were not classified into an individual SSMU, because we deemed them as areas that were too small to be of interest. In order to be classified as an SSMU, an area must have been noticeably large, or smaller areas must have been closely surrounded by other similar classified larger or smaller areas. To evaluate the change in SSMUs as the fields dried down the "zonal statistics to table" tool in ArcMap was used to calculate descriptive statistics (minimum, maximum, range, mean, SD, and CV) and total area [%; (total area of SSMU/total area of the field) x 100] of the SSMUs on each day of dry down within both fields.

Results

Descriptive statistics of VWC, penetration resistance, and NDVI on each day of dry down are presented in Table 5.1 and 5.2 for Oconee Park and North Oconee, respectively. VWC decreased 67% from day 1 ($\bar{x}$ = 21.3%) to day 11 ($\bar{x}$ = 7.1%) at Oconee Park and 33% from day 1 ($\bar{x}$ = 25.7%) to day 8 ($\bar{x}$ = 17.2%) at North Oconee. Penetration resistance increased 142% from day 1 ($\bar{x}$ = 5.3 MPa) to day 11 ($\bar{x}$ = 9.1 MPa) at Oconee Park and 119% from day 1 ($\bar{x}$ = 2.5 MPa) to day 8 ($\bar{x}$ = 3.1 MPa) at North Oconee. NDVI decreased 22% from day 1 ($\bar{x}$ = 0.67) to day 11 ($\bar{x}$ = 0.52) at Oconee Park and 8% from day 1 ($\bar{x}$ = 0.48) to day 8 ($\bar{x}$ = 0.44) at North Oconee.

VWC-penetration resistance correlation coefficients were negative at each location; however, the relationships were only significant at Oconee Park ($P < 0.001$). The VWC-penetration resistance relationship at Oconee Park was strong on day 1 and day 4 (r = -0.72 and -0.77, respectively), but moderate on day 11 (r = -0.45). At North Oconee the VWC-penetration resistance relationships were weak and remained relatively similar during dry down (*r* = -0.05, -0.09, and -0.07 on day 1, day 5, and day 8, respectively).

VWC-NDVI correlation coefficients were positive and generally weak at each location. The only significant VWC-NDVI relationships were at Oconee Park (day 1 and day 11). The strength of the relationship at Oconee Park decreased from day 1 [$r = 0.15$ ($P < 0.05$)] to day 4 ($r = 0.07$), but then increased on day 11 [$r = 0.34$ ($P < 0.001$)]. The VWC-NDVI relationships at North Oconee did not change significantly during dry down (*r* = 0.12, 0.08, and 0.14 on day 1, day 5, and day 8, respectively).

Penetration resistance-NDVI correlation coefficients were negative, weak to moderate, and significant at both locations during dry down. At Oconee Park the strength of relationship decreased from day 1 [$r = -0.25$ ($P < 0.001$)] to day 4 [$r = -0.17$ ($P < 0.05$)], but then increased on day 11 [$r = -0.39$ ($P < 0.001$)]. At North Oconee the penetration resistance-NDVI relationships increased from day 1 [$r = -0.25$ ($P < 0.01$)] to day 5 [$r = -0.45$ ($P < 0.01$)], but then decreased on day 8 [$r = -0.30$ ($P < 0.01$)].

The spherical model was the best fit for all semivariograms of VWC, penetration resistance, and NDVI on each day of dry down at Oconee Park (semivariograms not presented). The kriged maps of all measured properties on each day of dry down are displayed in Figure 5.1. It is apparent when examining the maps that dry down had significant influence on the magnitude of VWC, penetration resistance and NDVI. The strong to moderate relationship between VWC and penetration resistance is exemplified by their spatial maps. The generally weak relationship between VWC and NDVI on all days is also evident from the maps, because none show resemblances in variability across the field. The spatial distribution of penetration resistance and NDVI begin dissimilarly, but become more comparable with each subsequent day.

At North Oconee, VWC semivariograms were best fitted with the exponential model, while penetration resistance and NDVI semivariograms were best fitted with the spherical model (semivariograms not presented). Kriged maps of all properties on each day of dry down are displayed in Figure 5.2. The maps reveal that dry down had minimal influence on the magnitude of penetration resistance and NDVI, because areas within the field remained in similar legend classes [with exception of penetration resistance in the center (day 5 and day 8) and southeast corner (day 8), and NDVI in the southeast corner (day1)]. The weak relationships between VWC and penetration resistance, and VWC and NDVI, are also apparent by their different spatial distributions. However, the moderate relationship between penetration resistance and NDVI is noticeable.

The delineated SSMU maps of VWC, penetration resistance, and NDVI at Oconee Park and North Oconee on each day of dry down are displayed in Figure 5.3 and 5.4, respectively. Descriptive statistics and % area of each property within the respective SSMUs for each day of dry down at Oconee Park and North Oconee are presented in Table 5.3 and 5.4, respectively. At Oconee Park, the low VWC SSMUs on day 1 were in the southern and northeast area of the field; however, by day 11 they were located in the western and southeast sections. A distinct location in the southcentral part of the field remained as a high VWC SSMU each day. An additional high VWC SSMU appeared on day 4 and 11 in the northern portion of the field. The total area was dominated by the moderate VWC SSMU on day 1 (72.5% of the field), but then it decreased by day 11 (47.1% of the field); thus, low and high VWC SSMUs became larger as the field dried (15.9% to 26.0% and 11.6% to 26.9% of the field from day 1 to day 11 for low and high VWC SSMUs, respectively). The mean within each VWC SSMU classification decreased during dry down (18.9% to 5.6%, 21.5% to 7.0%, and 23.8% to 8.8% from day 1 to day 11 for the low, moderate, and high VWC SSMUs, respectively).

The low penetration resistance SSMUs on day 1 at Oconee Park was in the center and northeast corner of the field. On day 4 the low penetration resistance SSMU in the northern section extended nearly the width of the field, but by day 11 it only occupied the northeast corner, while the one from the center expanded to cover the eastern central section. Only a single high penetration resistance SSMU was located in the south end of the field on day 1; however, on day 4 a high penetration resistance SSMU also became evident in the northwest corner. On day 11 another high penetration resistance SSMU appeared in the western central location of the field. Similar to VWC, the total area of the field on day 1 was dominated by the moderate penetration resistance SSMU (18.9%, 61.8%, and 19.3% of the field for the low, moderate, and high penetration resistance SSMUs, respectively). Although by day 11 the total area for each penetration resistance SSMU became more evenly distributed (27.2%, 35.9%, and 36.9% of the field for the low, moderate, and high penetration resistance SSMUs, respectively). The mean within each penetration resistance SSMU classification increased during dry down (4.1 MPa to 7.9 MPa, 5.3 MPa to 9.3 MPa, and 6.5 MPa to 9.9 MPa from day 1 to day 11 for the low, moderate, and high penetration resistance SSMUs, respectively).

NDVI SSMUs remained the most stagnant of the measured properties during dry down at Oconee Park. The two low NDVI SSMUs remained in the northern and southern areas of the field. The only noteworthy difference was on day 4, when the northern SSMU did not expand the width of the field as it did on day 1 and 11. Three moderate NDVI SSMUs were observed each day in the northern, central, and southern locations of the field. There were high NDVI SMMUs in all corners with exception of the southwest. High NDVI SSMUs also occupied the central portion of the field, but only on day 4 did a large SSMU extend the width of the field. The total area of the low NDVI SSMUs remained similar from day 1 to day 11 (36.2% and 35.7% of the field, respectively). The moderate NDVI SSMUs increased (25.7% to 34.8% of the field from day 1 to day 11) and the high NDVI SSMUs decreased (38.1% to 29.5% of the field from day 1 to day 11). The mean within each NDVI SSMU classification decreased during dry down (0.63 to 0.47, 0.67 to 0.52, and 0.70 to 0.57 from day 1 to day 11 for the low, moderate, and high NDVI SSMUs, respectively).

At North Oconee, the low, moderate, and high VWC SSMUs each remained in the same vicinity during dry down. The low VWC SSMUs were in the western central and southeast, the moderate were in the center, southwest, and southeast, and the high was in the northern area of the field. The total area of each VWC SSMU changed minimally from day 1 to day 8 (20.6% to 25.7%, 43.6% to 39.3%, and 35.8% to 35.0% of the field for the low, moderate, and high VWC SSMUs, respectively). The mean within each VWC SSMU classification decreased during dry down (21.7% to 11.7%, 24.6% to 16.1%, and 29.4% to 22.4% from day 1 to day 8 for the low, moderate, and high VWC SSMUs, respectively).

On day 1 at North Oconee a large low penetration resistance SSMU occupied the northern and western area of the field with a smaller one to the southeast. By day 5 and day 8 the large low penetration resistance SSMU separated in two (located in the north and southwest) and smaller ones remained in the southeast. One moderate penetration resistance SSMU occupied the eastern side of the field on day 1 and a second arose in the western central portion of the field on day 5. By day 8, one large horseshoe shaped moderate penetration resistance SSMU wrapped around the center of the field. A high penetration resistance SSMU was located in the center of the field each day, but a second appeared on day 8 in the southeast corner. The total area for the low and high penetration resistance SSMUs decreased from day 1 to day 8 (37.3% to 25.9% and 33.5% to 26.7% of the field for the low and high penetration resistance SSMUs, respectively) and the moderate penetration resistance SSMUs increased (29.2% to 47.4% of the field from day 1 to day 8). The mean within all penetration resistance SSMU classifications increased from day 1 to 5 (2.1 MPa to 2.4 MPa, 2.5 MPa to 3.0 MPa, and 3.0 MPa to 3.5 MPa for the low, moderate, and high penetration resistance SSMUs, respectively). The low penetration resistance SSMU mean increased from day 5 to day 8 (2.4 MPa to 2.6 MPa), but the moderate and high penetration resistance SSMU means remained the same (3.0 MPa and 3.5 MPa, respectively).

Minimal changes in spatial distribution were observed for NDVI SSMUs at North Oconee during dry down. A small low NDVI SSMU was present in the southeast corner on day 1, but the two from the center and northeast corner remained each day. One large moderate NDVI SSMU circled the center of the field and four high NDVI SSMUs occupied the corners each day. The total area for the low and high NDVI SSMUs increased from day 1 to day 8 (24.9% to 29.9% and 27.1% to 32.4% of the field for the low and high penetration resistance SSMUs, respectively) and the moderate NDVI SSMUs decreased (48.0% to 37.7% of the field from day 1 to day 8). The mean within all NDVI SSMU classifications decreased from day 1 to 5 (0.40 to 0.35, 0.49 to 0.45, and 0.55 to 0.53 for the low, moderate, and high NDVI SSMUs, respectively). The moderate and high NDVI SSMU means decreased slightly from day 5 to day 8 (0.45 to 0.44 and 0.53 to 0.51, respectively), but the low NDVI SSMU mean remained the same (0.35).

Discussion

The first requirement for PTM is to obtain detailed site information. Performance testing is a general sports turf industry term given to site assessment protocols that are used to quantify field properties (McAuliffe 2008; Carrow et al. 2010). Previous performance testing research utilize descriptive statistics obtained from minimal sampling (5-12 locations within a field) to assess field safety and playability for the determination of performance standards. However, minimal strategies for field improvements were suggested (Bell and Holmes 1988; Canaway et al. 1990; McClements and Baker 1994; Baker et al. 2007). PTM requires more intensive data sampling to delineate SSMUs for the implementation of site-specific management to potentially reduce inputs and improve field uniformity (Carrow et al. 2010). The combination of performance testing and site-specific management is the foundation for PTM of natural turfgrass sports fields; however, standard sampling procedures must be in place to accurately identify spatiotemporal variability of sports field properties before performance testing can be considered as the site assessment aspect of PTM.

This study utilized the PS6000 and a 2.4 x 4.8 m sampling grid to obtain ~450-530 samples each day at both locations. To date, this is the most samples reported for spatial analysis of sports field properties. It should be noted that Oliver and Webster (2014) proposed that a minimum of 100 samples are needed to create a reliable semivariogram for kriging. Generally, the more samples collected the greater the accuracy. Other researchers have used handheld devices to record nearly 100 geo-referenced samples from sports fields for the creation of spatial maps. Caple et al. (2012) collected 135 or 150 samples (depending on the field; sampling grid size was not specified) of several properties on three soccer fields using handheld devices at the beginning, middle, and end of a season to evaluate spatiotemporal variability. Miller (2004) and Freeland et al. (2008) were able to detect the spatial variability of surface hardness on sports fields using only 80 (10.0 x 10.0 m sampling grid) and 77 (9.1 x 9.1 m sampling grid) samples, respectively, with a handheld Clegg Impact Soil Tester (CIST) (Lafayette Instrument Co., Lafayette, IN). Straw et al. (2016) compared mobile and handheld devices that measured VWC, penetration resistance, and NDVI for spatial analysis of natural turfgrass sports fields using two sampling grid sizes [4.8 x 4.8 m (230-259 samples) and 4.8 x 9.6 m (120-130 samples)]. Spatial maps of VWC and NDVI obtained from mobile and handheld data were highly comparable at detecting within-field variability with minimal differences observed between sampling grid sizes. Although accurate field property maps were generated with both handheld and mobile devices using various sampling procedures, SSMUs were not created.

In our research, general patterns of variability were comparable between maps of equal interval and SD-based legend classifications; however, the SD-based legend removed most small areas of differences and made locations of interest (high and low values) more detectable for SSMU delineation. The area within an SSMU should be more similar than the whole field, which should be reflected by a decrease in SD and CV (Krum et al. 2010). A decrease in SD and CV for VWC, penetration resistance, and NDVI was recognized from the whole field level to individual SSMU classes on each day, indicating sufficient SSMU delineation.

It is important to recognize that the SSMU boundaries created in our study do pose researcher bias. There are instances where SSMUs may be delineated differently based on interpretation. For example, the high penetration resistance SSMU along the southern end at Oconee Park on day 1 and day 4 of dry down could be divided into two high and one moderate SSMU, instead of one high SSMU. We believe if the SD-based maps are used as a guide then differences in delineation would generally be minor and our overall results would not be greatly influenced. It is our opinion that the human element for determining SSMUs boundaries is important. Ultimately, the turfgrass manager would have the most knowledge regarding their field; thus, the most useful SSMUs may be delineated by combining SD-based maps with the turfgrass manager's knowledge of the potential causation regarding within-field variations.

Evaluation of SSMUs during dry down resulted in spatiotemporal changes of VWC, penetration resistance and NDVI, especially on the native soil field (Oconee Park), which had higher clay content than the sand capped field (North Oconee). At Oconee Park, the magnitude of values within each SSMU class decreased for VWC and NDVI, and increased for penetration resistance, from day 1 to day 11. The strength of relationship during this time increased between VWC and NDVI, as well as penetration resistance and NDVI, while the relationship decreased between VWC and penetration resistance. This was exemplified when near field capacity the spatial distribution of the penetration resistance SSMUs most closely mirrored VWC SSMUs; however, as the field dried, the penetration resistance SSMUs reflected the combined effect of VWC and NDVI. Thus, sampling penetration resistance near field capacity appears to be strongly influenced by field drainage capabilities, but sampling penetration resistance under drier conditions more resembles both field drainage capabilities and wear patterns. The spatial distributions of NDVI SSMUs were not drastically altered due to dry down; therefore, sampling on any day may result in similar NDVI SSMU locations.

The spatiotemporal influence of soil drying on VWC, penetration resistance, and NDVI SSMUs was not as apparent at North Oconee. The magnitude of values within each VWC SSMU classification decreased from day 1 to day 8. All values for the penetration resistance SSMU classes increased minimally from day 1 to day 5, then remained relatively similar from day 5 to day 8. Inversely, the magnitude of values within each NDVI SSMU class decreased minimally from day 1 to day 5, then remained similar from day 5 to day 8. The strength of relationship between VWC and penetration resistance as well as VWC and NDVI was weak during dry down; therefore, the spatial distribution of VWC SSMUs were likely influenced by field drainage capabilities, but did not resemble penetration resistance or NDVI SSMUs. Penetration resistance closely resembled NDVI, even near field capacity, because the effect of soil moisture on penetration resistance was reduced (whereas VWC strongly influenced penetration resistance at Oconee Park). Areas of high penetration and NDVI SSMUs likely are the result of soil compaction and wear from foot traffic on the field. Higher correlation coefficients and similar spatial patterns of the penetration resistance and NDVI SSMUs support these observations. Two exceptions include a small high penetration resistance SSMU in the southeast corner on day 8 and a small low NDVI SSMU in the southeast corner on day 1. In general, sampling could have been performed on any day of dry down and produced similar spatial locations for all SSMUs.

At Oconee Park we were able to sample under short-term drought conditions (day 11 of dry down) due to irrigation restrictions. A limitation to our study was the North Oconee field was unable to dry down until symptoms of drought occurred. A longer dry down period at North Oconee could have resulted in a further decrease of VWC and NDVI, and an increase in penetration resistance. As a result, we may have observed changes to the SSMUs given drier soil conditions. Nonetheless, we do believe the 8 day dry down conducted at North Oconee provides an example of a practical dry down duration for sand capped sports fields.

To date, this is the only study that evaluated the spatiotemporal relationships between VWC, penetration resistance, and NDVI, and associated SSMUs, during a dry down on sports fields. Previous studies have observed similar relationship patterns and differences on fields constructed with varying soil textures, but none of these assessments were short-term or involved SSMUs. In a non-spatial study, Holmes and Bell (1986) calculated a -0.57 ($P < 0.001$) Pearson's r correlation coefficient between pooled soil moisture and penetration resistance data from seven fields (five of which were measured three times during the study duration). It was concluded that the two well-drained sand fields provided more consistent playing conditions (within the fields throughout the season) compared to the other five undrained medium-heavy soil fields. Similarly, a non-spatial study by Caple et al. (2012b) found soil water content and penetration resistance to be negatively correlated on six fields of varying soil textures from pooled data over 10 months [Pearson's r correlation coefficients ranged from not significant (-0.15) to significant (- 0.75 to -0.95; $P < 0.05$) on each field]. It was also found that the two sand fields exhibited more consistent penetration resistance over the studies duration than the four native soil fields (based on monthly means and CV). Caple et al. (2012a) mapped VWC and penetration resistance simultaneously on three soccer fields three times during a playing season and observed an inverse relationship based on descriptive statistics (correlation coefficients were determined, but not specifically reported). The sand based field in this study had more spatiotemporal consistency and smaller data ranges than the native soil fields (Caple et al. 2012a). Fine textured soils (native soil) have a higher water holding capacity and are more susceptible to soil compaction than course textured soils (sand), which is likely a reason for the recognized differences between fields in these studies (Beard 1972; Holmes and Bell 1986; Caple et al. 2012a, b).

Minimal studies involving NDVI spatial maps have been conducted in turfgrass and currently only one has been published *in-situ* on sports fields (Carrow et al. 2010; Krum et al. 2010; Straw et al. 2016). Comparison of our results is difficult, because Straw et al. (2016) did not measure NDVI over time on the sports fields evaluated in their work. Several studies have concluded that NDVI is a useful tool to objectively differentiate between visually stressed and nonstressed turfgrass (Trenholm et al. 1999; Jiang and Carrow 2005; Jiang and Carrow 2005;

Bremer et al. 2011). From these reports we hypothesize that short-term changes in NDVI may be due to major sporting/non-sporting events or severe drought. Long-term changes could also occur for these reasons, but within-field spatial variations in NDVI may change through time based on field usage, management, and weather conditions prior to sampling.

The most practical applications for sports field SSMUs may be site-specific irrigation and aerification. Mapping after rainfall provides insight into the drainage capability of a field and subsequent identification of areas with poor water infiltration or higher water holding capacities (e.g. the distinct location in the southcentral part of the field at Oconee Park that remained a high VWC SSMU throughout the dry down). This can be valuable information for the prevention of puddling and cancelation of sporting events. It may be useful to soil sample within SSMUs to identify potential differences in soil texture across the field, which may have an influence on the water infiltration or holding capacity in certain areas.

It would be difficult to use the maps in this study to delineate VWC SSMUs for site-specific irrigation. Mapping under dry conditions, when the only source of soil moisture is from irrigation, would help locate malfunctioning irrigation heads for corrective maintenance. Carrow et al. (2010) noted that mapping dry down after irrigation could aid in site-specific irrigation by determining the number of days until 50% field capacity is reached within each VWC SSMU then scheduling irrigation zones to run accordingly. Collecting NDVI measurements simultaneously may allow for the identification of malfunctioning irrigation heads and differentiation from wear damage (Krum et al. 2010).

Mapping after rainfall to delineate penetration resistance SSMUs is most appropriate for site-specific aerification. Flitcroft et al. (2010) mapped penetration resistance on a golf course fairway after rainfall, and during a drier period (soil moisture based solely on irrigation), and concluded mapping penetration resistance under drier conditions in order to conduct site-specific aerification can be misleading due to the strong influence of irrigation efficiency. Mapping after rainfall ensures a more uniform application of water and eliminates the effect of irrigation system deficiencies on penetration resistance. Our results indicated that penetration resistance SSMUs on a native soil field immediately following rain initially resembled field drainage capabilities; however, as the field dried, SSMUs resembled the combination of field drainage capabilities and wear patterns. Sampling penetration resistance after rainfall for site-specific aerification should depend on the objective. On the sand based field soil moisture had minimal influence on penetration resistance SSMUs. This is an indication that sampling could be done any time during dry down from rainfall. The weak correlation between VWC and penetration resistance suggests that penetration resistance SSMUs may also be delineated also after irrigation on sand based fields, but further research is necessary for verification.

Prior to using SSMUs for site-specific aerification, penetration resistance values must be determined to be at a reasonable level. If the low or high penetration resistance SSMUs exceed a certain threshold then whole-field management may be initially required. A penetration resistance limit within SSMUs (> 3.99 MPa) was proposed by Flitcroft et al. (2010) to determine site-specific aerification implementation in heavily compacted areas on a golf course fairway. Based on this recommendation, each penetration resistance SSMU at Oconee Park would have exceeded the 3.99 MPa limit on each day of dry down and the entire field would require aerification. Unfortunately, no thresholds exist to trigger site-specific aerification on sports fields. Additionally, soil moisture at time of sampling should be considered, since penetration resistance may be below thresholds when the field is near field capacity and above thresholds when the field is drier.

Furthermore, utilizing SSMUs can provide a more precise, within-field assessment of player safety and field playability. Surface hardness and traction (the amount of footwear grip on the turf) are the two primary properties associated with injuries on natural turfgrass sports fields (Nigg and Segesser 1988; Ekstrand and Nigg 1989; Milburn and Barry 1998). Surface hardness is highly correlated (inversely) with soil moisture (Bell and Holmes 1988; Baker 1991); whereas traction is highly correlated with ground cover (which can be assessed with NDVI) (Holmes and Bell 1986; Baker 1991; McClements and Baker 1994). Ball roll and ball bounce are components of field playability (Bell et al. 1985; Canaway and Baker 1993). Ball roll is correlated with ground cover (inversely) and surface hardness (Bell and Holmes 1988; McClements and Baker 1994), while ball bounce is correlated with soil moisture (inversely), penetration resistance, surface hardness, and ground cover (inversely) (Holmes and Bell 1986; Baker and Isaac 1987; Bell and Holmes 1988). Understanding these relationships is valuable for subsampling within correlated SSMUs, especially if it is not feasible to obtain maps for all properties of interest. For example, areas most likely to have the highest surface hardness will be the driest; therefore, subsampling surface hardness within low VWC SSMUs would be useful for assessing hardness levels. Site-specific irrigation could become a viable option to temporarily increase soil moisture and reduce surface hardness before gameplay, due to the inverse relationship between the two. This theory has not been tested and warrants further investigation, but one concern is that most sports field irrigation systems do not have single-head control. Additionally, turfgrass managers should determine at which soil moisture levels to subsample based on what they believe to be typical field conditions, since soil moisture influences a number of sports field properties.

The aforementioned practical applications of SSMUs can be extended between field's at large sports complexes. Carrow et al (2010) reported that an entire golf course may have 4-6 or more distinct SSMUs, with 2-3 on a single fairway. It would be reasonable to hypothesize a potential for similar SSMUs across sports fields at the same complex, especially those constructed of the same soil type. Mapping an entire complex and generating SSMUs across fields would be extremely beneficial for identifying deficient areas to implement PTM; however, a current restraint may be the limited availability of mobile sampling devices for mapping large areas in a time and labor efficient manner.

Conclusion

Natural turfgrass sports fields exhibit spatiotemporal variations. Implementing PTM could reduce inputs, improve field variability, and provide a more safe and predictable playing surface. A key component of PTM is delineation of SSMUs that can be used to identify areas of interest for site-specific management applications or as an improved sampling strategy to assess field safety. This was the first study to evaluate the spatiotemporal variations of SSMUs and how the change may influence PTM applications on native soil and sand capped natural turfgrass sports fields. The native soil field did not dry down uniformly. In general, the magnitude of VWC SSMUs and NDVI SSMUs decreased, while penetration resistance SSMUs increased as the field dried. This trend was amplified on the native soil field. Significant changes in spatial distributions were observed during dry down for VWC SSMUs and penetration resistance SSMUs on the native soil field; however, minimal changes were detected on the sand capped field. This suggests that sampling could have been performed on any day of dry down on the sand capped field and produced similar spatial locations for VWC and penetration resistance SSMUs The spatial distributions of NDVI SSMUs were minimal on both fields each day. In conclusion, short-term spatiotemporal variations of SSMUs on sports fields during a dry down can be significant. Soil moisture can influence the magnitude and spatial distribution of SSMUs and should be strongly considered when determining sample timing.

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Table 5.1 Descriptive statistics of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) for each day of dry down[a] at Oconee Veterans Park (sandy loam soil).

	Day	Sample size	Minimum	Maximum	Range	Mean	Standard deviation	CV (%)
			%					
VWC	1	528	4.3	32.4	28.1	21.3	4.6	21.6
	4	530	3.4	24.8	21.4	13.6	4.4	32.4
	11	529	0.6	18.9	18.4	7.1	3.1	43.7
			MPa					
PR	1	528	1.4	10.1	8.7	5.3	2.3	43.4
	4	530	2.6	10.4	7.8	7.3	2.2	30.1
	11	529	3.9	11.0	7.1	9.1	1.7	18.7
NDVI	1	528	0.44	0.81	0.37	0.67	0.06	9.0
	4	530	0.38	0.78	0.40	0.63	0.07	11.1
	11	529	0.30	0.75	0.45	0.52	0.08	15.4

[a] Approximately 15 mm of rainfall occurred the day prior to initial data collection. Day 1, 4, and 11 indicate the number of days after rainfall, respectively. No additional rainfall or irrigation occurred during dry down.

Table 5.2 Descriptive statistics of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) for each day of dry down[a] at North Oconee High School (sand cap).

	Day	Sample size	Minimum	Maximum	Range	Mean	Standard deviation	CV (%)
			———	———	%	———	———	
VWC	1	450	15.3	35.2	19.9	25.7	4.0	15.6
	5	450	7.1	32.4	25.3	21.2	5.1	24.1
	8	450	4.0	31.3	27.3	17.2	5.6	32.6
			———	———	MPa	———	———	
PR	1	450	1.1	4.3	3.2	2.5	0.7	28.0
	5	450	1.4	5.2	3.8	3.0	0.7	23.3
	8	450	1.2	5.3	4.1	3.1	0.7	22.6
NDVI	1	450	0.15	0.70	0.55	0.48	0.11	22.9
	5	450	0.18	0.65	0.47	0.44	0.11	25.0
	8	450	0.20	0.64	0.44	0.44	0.10	22.7

[a] Approximately 46 mm and 5 mm of rainfall occurred six and three days prior to initial data collection, respectively. The heavy rainfall caused puddling in areas and data collection did not initiate until excess water had drained and the field was at or near field capacity. Day 1, 5, and 8 indicate the number of days after the field had drained, respectively.

Table 5.3 Descriptive statistics of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) in site-specific management units (SSMUs) for each day of dry down[a] at Oconee Veterans Park (sandy loam).

	Day	SSMU[b]	Minimum	Maximum	Range	Mean	Standard deviation	CV (%)	Area[c] (%)
			———	———	%	———	———		
VWC	1	Low	13.9	22.7	8.8	18.9	1.5	7.9	15.9
		Moderate	18.5	24.1	5.6	21.5	0.9	4.1	72.5
		High	20.8	26.2	5.4	23.8	1.1	4.6	11.6
	4	Low	7.7	14.6	6.9	11.3	1.5	13.3	17.1
		Moderate	10.6	16.3	5.7	13.5	1.1	8.1	63.4
		High	12.0	20.5	8.5	16.1	1.7	10.6	19.5
	11	Low	3.2	7.4	4.2	5.6	0.7	12.5	26.0
		Moderate	5.7	8.5	2.8	7.0	0.5	7.1	47.1
		High	6.0	13.1	7.1	8.8	1.3	14.8	26.9
			———	———	MPa	———	———		
PR	1	Low	3.1	5.8	2.7	4.1	0.5	12.2	18.9
		Moderate	3.9	7.1	3.2	5.3	0.6	11.3	61.8
		High	4.5	8.1	3.6	6.5	0.7	10.8	19.3
	4	Low	4.5	8.3	3.8	6.2	0.6	9.7	33.1
		Moderate	6.3	8.7	2.4	7.4	0.5	6.8	36.6
		High	6.6	9.7	3.1	8.4	0.6	7.1	30.3
	11	Low	6.5	9.3	2.8	7.9	0.6	7.6	27.2
		Moderate	8.1	10.2	2.1	9.3	0.4	4.3	35.9
		High	8.4	10.7	2.3	9.9	0.4	4.0	36.9
NDVI	1	Low	0.57	0.69	0.12	0.63	0.02	3.2	36.2

	Moderate	0.64	0.70	0.06	0.67	0.01	1.5	25.7
	High	0.65	0.75	0.10	0.70	0.02	2.9	38.1
4	Low	0.50	0.64	0.14	0.58	0.02	3.4	25.3
	Moderate	0.59	0.67	0.08	0.63	0.02	3.2	42.9
	High	0.64	0.74	0.10	0.68	0.02	2.9	31.8
11	Low	0.41	0.55	0.15	0.47	0.02	4.3	35.7
	Moderate	0.48	0.56	0.07	0.52	0.02	3.8	34.8
	High	0.49	0.64	0.15	0.57	0.02	3.5	29.5

[a] Approximately 15 mm of rainfall occurred the day prior to initial data collection. Day 1, 4, and 11 indicate the number of days after rainfall, respectively. No additional rainfall or irrigation occurred during dry down.

[b] Low, moderate, and high refer to the L, M, and H areas, respectively, in Figure 5.3.

[c] Area = (total area of SSMU/total area of the field) x 100.

Table 5.4 Descriptive statistics of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) within site-specific management units (SSMUs) for each day of dry down[a] at North Oconee High School (sand cap).

	Day	SSMU[b]	Minimum	Maximum	Range	Mean	Standard deviation	CV (%)	Area[c] (%)
			%						
VWC	1	Low	19.2	23.6	4.4	21.7	1.0	4.6	20.6
		Moderate	19.9	27.7	7.8	24.6	1.3	5.3	43.6
		High	23.5	33.0	9.5	29.4	1.7	5.8	35.8
	5	Low	11.5	19.6	2.1	15.8	1.8	11.4	25.2
		Moderate	16.4	24.0	7.6	20.5	1.7	8.3	40.2
		High	20.0	29.4	9.4	26.0	2.0	7.7	34.6
	8	Low	7.7	15.7	8.0	11.7	1.6	13.7	25.7
		Moderate	10.6	21.4	10.8	16.1	2.0	12.4	39.3
		High	15.7	27.8	12.1	22.4	2.7	12.1	35.0
			MPa						
PR	1	Low	1.5	2.8	1.3	2.1	0.2	9.5	37.3
		Moderate	2.0	3.0	1.0	2.5	0.2	8.0	29.2
		High	2.3	3.9	1.6	3.0	0.3	10.0	33.5
	5	Low	1.8	3.0	1.2	2.4	0.3	12.5	33.2
		Moderate	2.7	3.4	0.7	3.0	0.2	6.7	36.2
		High	2.8	4.3	1.5	3.5	0.3	8.6	30.6
	8	Low	2.0	3.2	1.2	2.6	0.2	7.7	25.9
		Moderate	2.2	3.6	1.4	3.0	0.2	6.7	47.4
		High	2.9	4.5	1.6	3.5	0.3	8.6	26.7
NDVI	1	Low	0.29	0.51	0.22	0.40	0.04	10.0	24.9

	Moderate	0.44	0.55	0.11	0.49	0.02	4.1	48.0
	High	0.49	0.63	0.14	0.55	0.02	3.6	27.1
5	Low	0.24	0.46	0.22	0.35	0.04	11.4	29.1
	Moderate	0.39	0.50	0.11	0.45	0.02	4.4	40.1
	High	0.45	0.60	0.15	0.53	0.03	5.7	30.8
8	Low	0.26	0.45	0.19	0.35	0.04	11.4	29.9
	Moderate	0.40	0.49	0.09	0.44	0.02	4.5	37.7
	High	0.44	0.59	0.15	0.51	0.03	5.9	32.4

[a] Approximately 46 mm and 5 mm of rainfall occurred six and three days prior to initial data collection, respectively. The heavy rainfall caused puddling in areas and data collection did not initiate until excess water had drained and the field was at or near field capacity. Day 1, 5, and 8 indicate the number of days after the field had drained, respectively.

[b] Low, moderate, and high refer to the L, M, and H areas, respectively, in Figure 5.4.

[c] Area = (total area of SSMU/total area of the field) x 100.

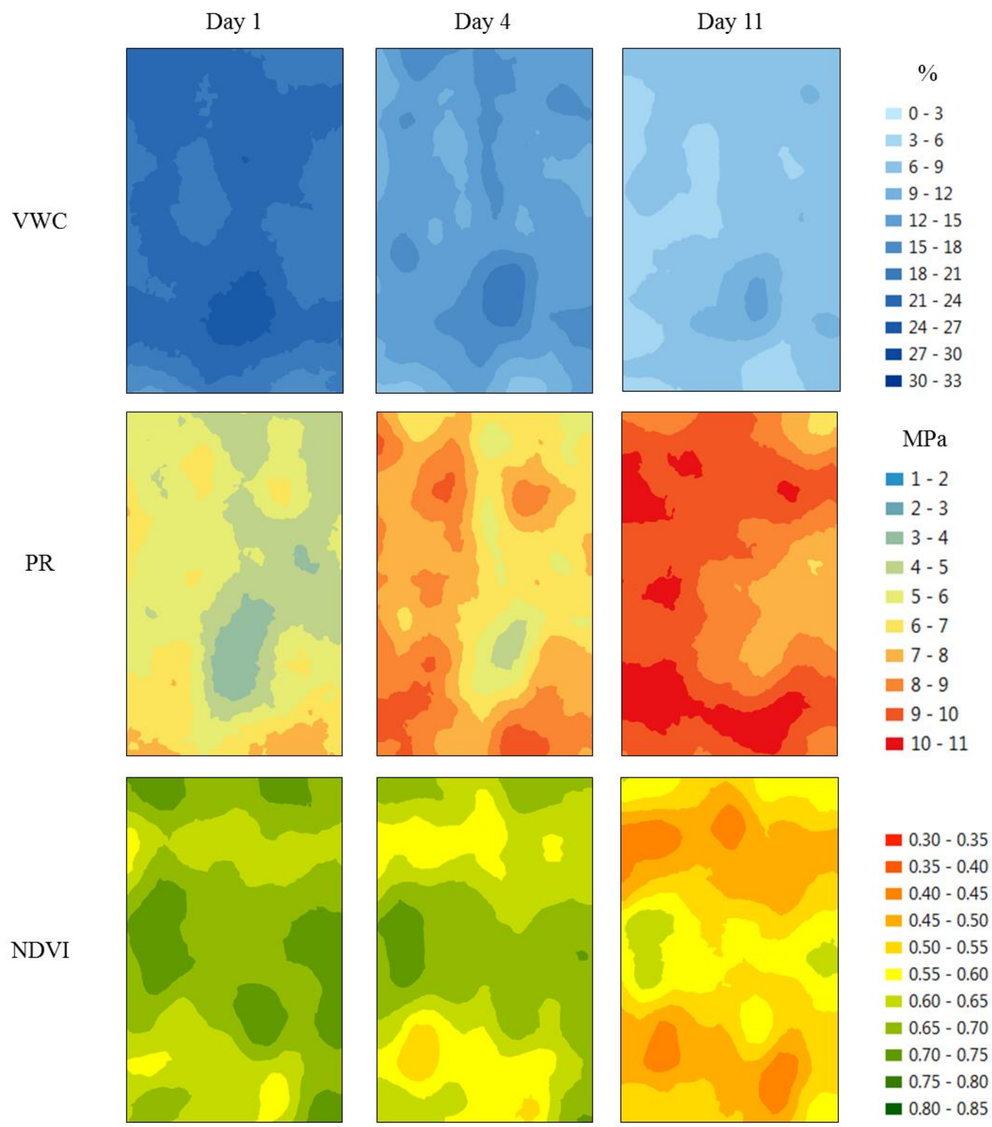

Figure 5.1 Kriged maps, with equal interval legend classifications, of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) on day 1, day 4, and day 11 of dry down after rainfall at Oconee Veterans Park (61.0 m wide and 97.5 m long; sandy loam soil). VWC, PR, and NDVI are in rows (top to bottom, respectively) and day of dry down are in columns (day 1, day 4, and day 11 from left to right, respectively).

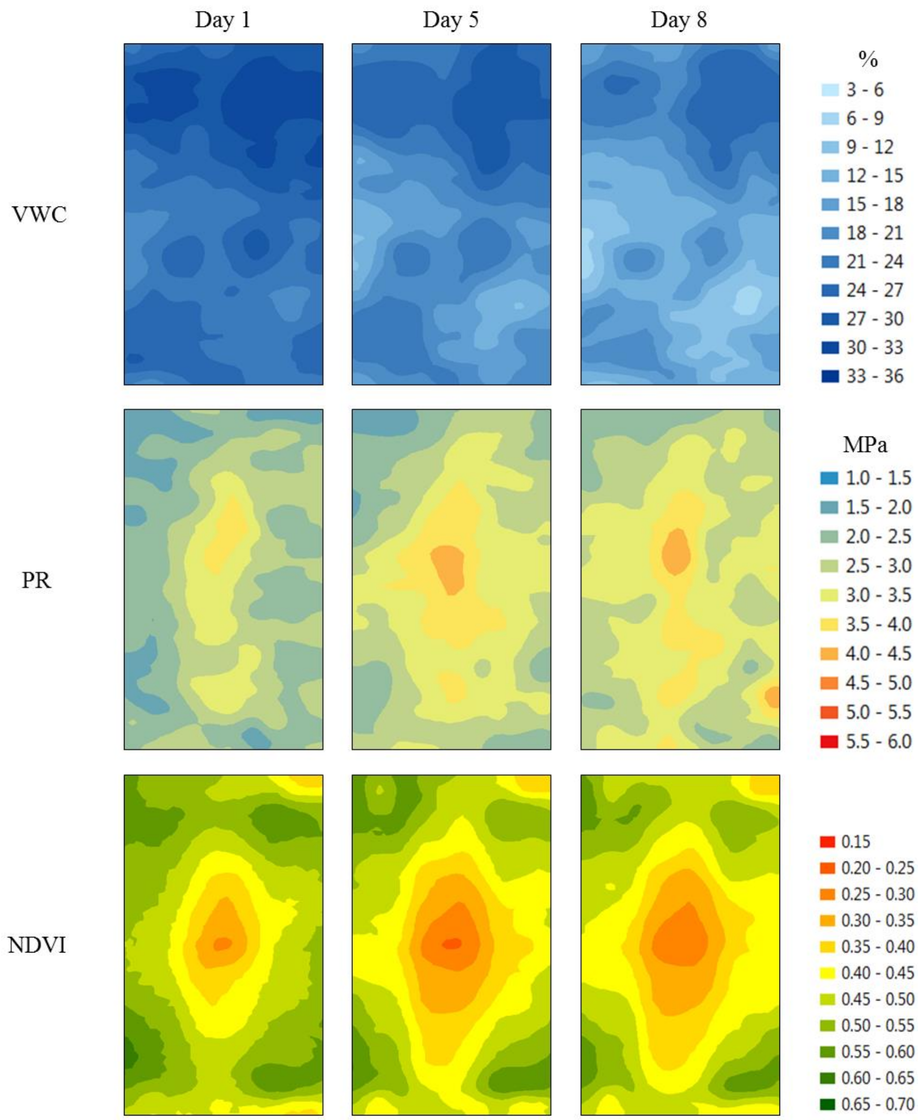

Figure 5.2 Kriged maps, with equal interval legend classifications, of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) on day 1, day 5, and day 8 of dry down after rainfall at North Oconee High School (48.8 m wide and 109.7 m long; sand capped soil). VWC, PR, and NDVI are in rows (top to bottom, respectively) and day of dry down are in columns (day 1, day 5, and day 8 from left to right, respectively).

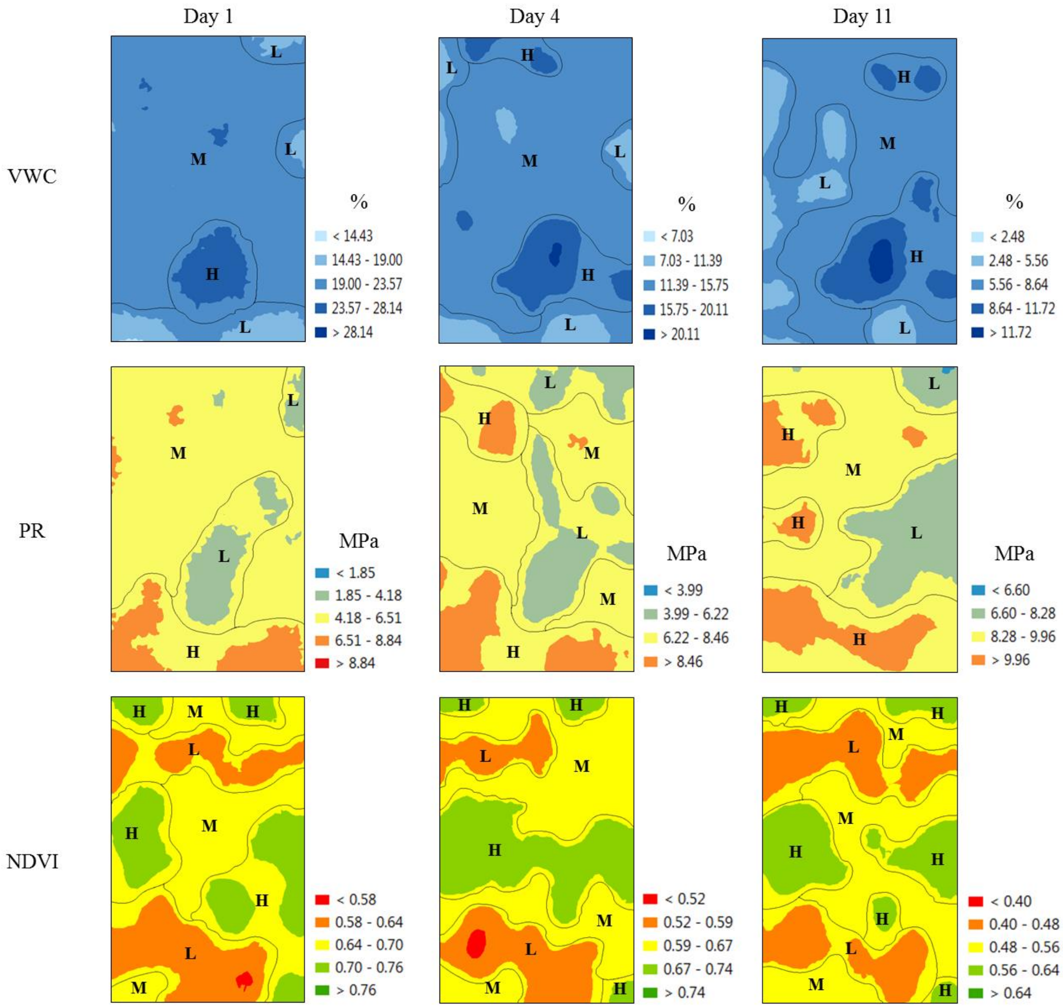

Figure 5.3 Site-specific management units (SSMUs) of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) on day 1, day 4, and day 11 of dry down after rainfall at Oconee Veterans Park (61.0 m wide and 97.5 m long; sandy loam soil). VWC, PR, and NDVI are in rows (top to bottom, respectively) and day of dry down are in columns (day 1, day 4, and day 11 from left to right, respectively). SSMUs were delineated from SD-based legend classifications maps. Low, moderate, and high SSMUs are denoted as L, M, and H, respectively.

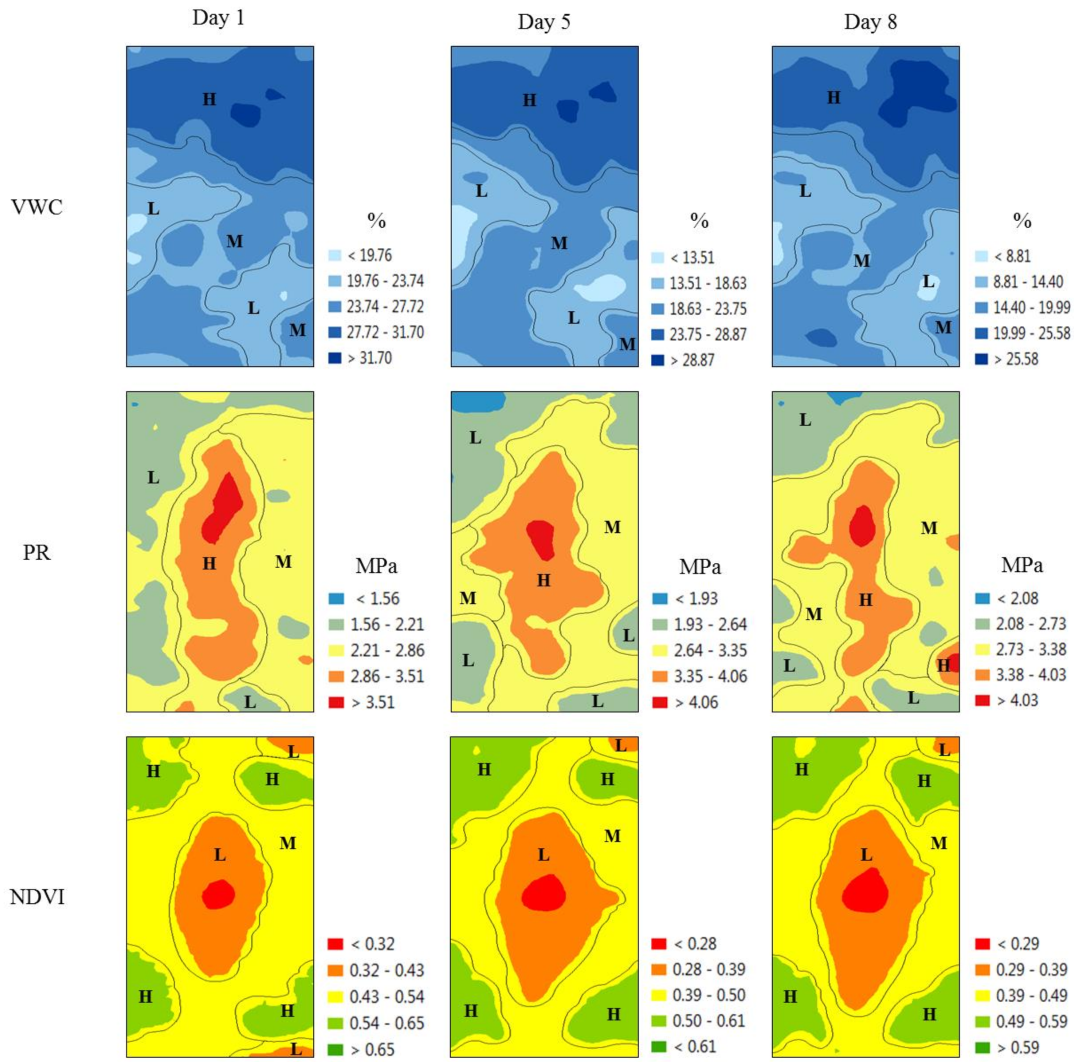

Figure 5.4 Site-specific management units (SSMUs) of volumetric water content (VWC), penetration resistance (PR), and normalized difference vegetative index (NDVI) on day 1, day 5, and day 8 of dry down after rainfall at North Oconee High School (48.8 m wide and 109.7 m long; sand capped field). VWC, PR, and NDVI are in rows (top to bottom, respectively) and day of dry down are in columns (day 1, day 5, and day 8 from left to right, respectively). SSMUs were delineated from SD-based legend classifications maps. Low, moderate, and high SSMUs are denoted as L, M, and H, respectively.

CHAPTER 6

CONCLUSIONS

Within-field variations of natural turfgrass sports field properties are inevitable due to foot traffic, field construction, management, and weather. Little is known about the influence that these variations have on athletes' perceptions and injury occurrence. Furthermore, minimal work has been conducted on natural turfgrass sports fields to further the concept of Precision Turfgrass Management (PTM), which may mitigate within-field variations. The four studies conducted in this dissertation investigated athletes' perceptions (Chapter 2) and injury occurrence (Chapter 3) related to within-field variability, as well as set out to increase knowledge about the spatiotemporal relationships between field properties (Chapter 4) and changes in site-specific management unit (SSMU) delineation during field dry down (Chapter 5).

A case study using qualitative and quantitative methods was conducted in Chapter 2 to better understand athletes' perceptions of within-field variability on natural turfgrass sports fields. Geo-referenced normalized difference vegetation index, surface hardness, and turfgrass shear strength data were obtained from a recreational-level sports field to create hot spot maps for identification of significant within-field variations. Twenty-five male and female collegiate Club Sports rugby and ultimate frisbee athletes participated in walking interviews (*in-situ*) to develop knowledge about athletes' perceptions of within-field variability. The quantitative (field data and hot spot maps) and qualitative (athlete interview responses) data were triangulated to explore, compare, and validate findings. It was found that athletes' perceptions of within-field variability generally corresponded with measured surface properties. Athletes perceived within-field variations of turfgrass coverage and surface evenness to be most important. Athletes were aware of the potential influences within-field variations could have, but not all made behavior changes. When changes were reported, athletes did so with regard to athletic maneuvers and/or strategy, primarily for safety or context of play (pre-game, practice, or game).

A preliminary study was conducted in Chapter 3 to determine if there is a relationship between within-field variations of natural turfgrass sports field properties and ground-derived athlete injuries. Ground-derived injuries of collegiate Club Sport athletes were self-reported over two years. Geo-referenced measurements of soil moisture, turfgrass quality, surface hardness, and turfgrass shear strength were obtained weekly or bi-weekly from the teams' two home fields (both recreational-level). Hot spot analysis was used each month to identify significantly high (hot spots) and low (cold spots) values within each field for comparison to ground-derived injury locations. Binomial proportion tests were conducted to determine if the observed proportion of injuries that occurred in significant areas was similar to expected proportions (i.e. the proportion of the field that was a hot and/or cold spot). Twenty-three ground-derived injuries were reported overall. The highest proportion occurred within a hot or cold spot of turfgrass quality, followed by soil moisture, and then surface hardness and turfgrass shear strength. The observed proportion of injuries occurring in turfgrass quality cold spots and soil moisture hot spots was significantly different than expected. Interestingly, most injuries occurring in significantly high or low areas of turfgrass quality, soil moisture, and surface hardness were located along edges of hot and cold spots.

Chapter 4 evaluated the spatiotemporal relationship of several sports field properties to aid in efficient sampling for spatial map creation to potentially improve field uniformity with PTM. Several geo-referenced field properties were measured from two sports fields comprised of sandy loam and sand capped soils before and after irrigation. Correlation coefficients and spatial maps were employed to investigate the spatiotemporal relationship of the properties at each field. It was found that minimal changes in strength of relationships and spatial maps occurred from before irrigation to after irrigation on both fields. Several significant relationships between properties were observed, although significance did not always result in comparable maps. Certain significant relationships and comparable spatial maps between properties were not the same on both fields. Volumetric water content had the most similar spatial maps with other properties in the native soil field and spatial maps of penetration resistance, NDVI, and surface hardness were similar in both fields.

Lastly, Chapter 5 examined the spatiotemporal change of soil moisture, penetration resistance, and NDVI SSMUs during a dry down from rainfall on native soil and sand capped natural turfgrass sports fields. Geo-referenced data were measured 3 times at each location during the dry downs. The relationship of penetration resistance and NDVI with VWC was strongest and only significant on the native soil field. The magnitude of VWC SSMUs and NDVI SSMUs decreased, while the magnitude of penetration resistance SSMUs increased as the fields dried. This phenomenon was more drastic on the native soil field. Significant changes in spatial distributions were observed for VWC SSMUs and penetration resistance SSMUs on the native soil field during dry down; however, minimal changes were reported on the sand capped field. The spatial distributions of NDVI SSMUs were minimal on both fields as they dried down.

It is concluded that within-field variations can have a significant impact on athletes' perceptions and injury occurrence, specifically on recreational-level fields. These results suggest that future studies evaluating athlete-surface interactions should incorporate details regarding within-field variations. Particularly, studies pertaining to athlete injuries, because there appears to be an association. New methodologies were introduced in Chapters 2 and 3 that would be highly beneficial for future studies. These results also justify the need for future research on Precision Turfgrass Management. Key surface properties and suggested sampling strategies from each study may be useful for its progression and implementation on natural turfgrass sports fields.