SPATIAL MAPPING OF PENETROMETER RESISTANCE ON TURFGRASS SOILS FOR SITE-SPECIFIC CULTIVATION

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ABSTRACT

Site-specific management requires site-specific information. High soil strength at field capacity, whether from inherent soil type or compaction, is a major stress on recreational turfgrass sites that requires frequent cultivation. Spatial mapping of penetrometer resistance (PR) at field capacity could allow site-specific cultivation; thereby, reducing labor, energy, and equipment wear. Spatial mapping of PR and volumetric soil water content (VWC) in the surface 10 cm was conducted on a golf course fairway under field capacity and dry conditions using a multiple-sensor mobile platform (TMM, Toro Company, Bloomington, MN) with GPS capability for: a) rapid measurement of surface zone VWC by time domain reflectrometer and b) soil strength by PR using two custom stainless steel probes of 9.53-mm diameter, 3.3-cm spacing, and 10-cm length installed on the moisture sensor to facilitate a soil penetration depth of 10 cm. Recording of PR was by a compression load cell. The TMM was affixed to and maneuvered with a utility vehicle, traversing the area by making passes at approximately 2.5-m spacing with measurements every 2.5 m in a traverse at an operating speed of 2.7 to 3.3 km h^{-1} with measurements made while the TMM is moving. When mapping at field capacity, PR was primarily related to soil type and localized areas of traffic concentration with a PR range of 2.4 to 5.8 MPa. To identity site-specific cultivation areas, a PR limit could be established, such as PR > 3.99 MPa to trigger cultivation. Mapping under drier conditions, resulted in PR being affected primarily by spatial variability of soil VWC in response to irrigation system distribution patterns; and thus less useful for determining site-specific cultivation areas.

Keywords: Soil compaction, precision turfgrass management, PTM, site-specific management, penetrometer

INTRODUCTION

Soil compaction is the pressing together of soil particles and aggregates into a more dense mass with reduced macropore space and aeration, while microporosity and soil strength increase. Additionally, many high-clay content soils exhibit properties similar to compacted soils with lower macroporosity and aeration and greater microporosity and soil strength relative to silt or sand dominated soil types. Also, fine-textured soils are prone to compaction. Compaction and excessively fine-textured soils are major problems in traditional agriculture with negative effects on production and the environment (Unger and Kasper, 1994; Hamza and Anderson, 2005). Maintenance vehicle and human traffic on recreational turfgrass sites also cause soil compaction with adverse effects on the turfgrass ecosystem, especially on fine-textured soils (Carrow and Petrovic, 1992).

Compaction in agricultural fields can arise from natural and man-induced practices and spatially vary across the landscape and within a soil horizon. Surface compaction may occur in wheel tracks of row crops or in general across a pasture from livestock, while deeper compacted zones may arise from heavy equipment, plow layers, or natural horizons (Spoor, 2006). On turfgrass recreational sites, soil compaction in the top 10 cm zone is the most persistent compaction problem due to frequent traffic.

In turfgrass and agricultural sites, soil compaction is often alleviated by cultivation operations with the type of cultivation equipment specific to the depth of compaction with degree of surface disruption another factor for turf areas (Carrow and Petrovic, 1992; McCarty, 2001; Spoor, 2006). Additionally, on irrigated turfgrass sites, especially with fine-textured soils, cultivation is often conducted to enhance water infiltration and percolation, reduce soil strength for rooting, and to enhance aeration. The relationship between soil strength and plant rooting suggests that when using a standard penetrometer cone with a 30° angle and a base of 12. 8 mm diameter cone on a 9.8 mm diameter shaft that PR values (ASAE Standards, 2005): a) between 2.00 to 3.00 MPa represent a very dense soil with few roots penetrating; and b) at > 3.00 MPa root growth virtually ceases (Unger and Kaspar, 1994; Hazelton and Murphy, 2007). However, others have reported higher PR values of 3.7 to 5.0 MPa before root growth ceases for barley (Hadas, 1997) and wheat (Masle and Passioura, 1987).

In both agriculture and turf areas, soil compaction and excessively fine-textured soils exhibit considerable spatial and temporal variation. As a component of Precision Agriculture (PA), research continues to be targeted to assessing spatial variation of soil strength, whether due to compaction or soil strength inherent in excessively high-clay content soils, in agriculture fields by various sensor systems (Hemmat and Adamchuk, 2008). The vertically operated cone penetrometer reported as cone index (CI, the force per unit base area required to push the penetrometer to a defined soil depth) has been widely used to measure soil strength, defined as mechanical impedance to a penetrating object. Penetrometer values are influenced by soil factors such as structure, bulk density, texture, and water content. Challenges in using traditional cone penetrometers in agriculture fields are: a) determining readings by soil depth requires repeated stopping; b) several readings are required at a discrete location to provide a reasonable average, and c) since soil moisture has a marked affect on readings, moisture data are important to interpret penetration resistance data.

In response to the problems associated with vertically operated cone penetrometers, a recent focus in PA has been toward sensor systems designed to determine soil strength spatially while the sensor platform moves across a field and with attention to different profile depths since subsurface compacted zones may restrict crop rooting (Adamchuk et al., 2004; Sudduth et al., 2008). Horizontally operated penetrometers are used on some of the systems. Increasingly, multiple sensor arrays have been investigated to provide information on soil moisture along with soil strength determinations due to the inverse relationship of soil strength and soil moisture (Unger and Kaspar, 1994; Yurui et al., 2008; Zeng et al., 2008).

Assessing surface conditions of sports fields as related to player safety and playability of the sport has received considerable attention where the combination of these is called “performance testing” (Baker and Canaway, 1993; McAuliffe, 2008; Stiles et al., 2009). Player safety standards include surface hardness and traction, while ball interaction entails rebound height, smoothness, and speed of roll. The Clegg hammer, a decelerometer device adopted from the road surfacing industry, is widely used to determine surface hardness (term used in turf industry rather than soil strength), while the penetrometer has also been used, especially in the horse racing tracks as the “Going Stick” (McAuliffe, 2008). Other devices are noted in the review by Stiles et al (2009). Measurements are generally taken at several key areas on sports fields or race tracks but not on an intensive, closely spaced grid since the devices are not mounted on mobile platforms but are hand-held units. Thus, geostatistical treatment of data is rare on individual sports fields and certainly on larger areas.

Mobile devices capable of determining key turfgrass surface properties with closely spaced, GPS labeled measurements would allow geostatistical assessment of spatial relationships and development of GIS maps. One application for soil strength and soil moisture measurements could be for site-specific cultivation in contrast to whole-area cultivation; thereby, saving energy, labor, and equipment wear costs (Carrow et al., 2010). The Toro Company (Bloomington, MN) developed a mobile platform (Toro Mobile Multiple-Sensor, TMM) with GPS capability for: a) rapid measurement of surface zone volumetric water content (VWC) by time-domain reflectrometer; and b) cone penetrometer resistance (PR) for soil strength mapping. The purpose of this paper is to present results from mapping of a golf course fairway with application for using soil strength maps to guide site-specific cultivation.

MATERIALS AND METHODS

The study was conducted at the Keller Golf Course, Maplewood, MN on fairway 1, an area of Kentucky bluegrass (*Poa pratensis*) and annual bluegrass (*Poa annua* L.) mowed three times weekly at a height of 1.50 cm with a reel mower. The fairway soil consists of areas of Brill silt loam, Chetek sandy loam, and urban land-Chetek complex. Data collection on 2 May 2007 followed significant rain events to bring the soil to field capacity, while the mapping on 2 July 2007 followed a prolonged dry period where soil moisture reflected the irrigation system distribution and scheduling.

Data collection was performed via the Toro Mobile Multi-Sensor (TMM; patent pending) prototype data acquisition unit (The Toro Company, Bloomington, MN). The TMM was affixed to and maneuvered with a utility vehicle, traversing the fairways by making passes at approximately 2.5-m spacing with measurements every 2.5 m in a traverse at an operating speed of 2.7 to 3.3 km h^{-1} with measurements made while the TMM is moving.. Data were recorded using an on-board laptop computer and all parameters were displayed in spreadsheet format. Data were obtained during the afternoon of each day within a time period of 1400 to 1800 h EST. Soil moisture measurements were based on time-domain reflectrometry (TDR), which measures changes in the soil dielectric constant (ε) as water contents fluctuate (Leib et al., 2003). A Field Scout TDR 100 soil moisture sensor (Spectrum Technologies, Inc. Plainfield, IL) was modified for use on the TMM platform and measured VWC at a 0- to 10-cm depth. Two custom stainless steel probes of 9.53-mm diameter, 3.3-cm spacing, and 10-cm length were installed on the moisture sensor to facilitate a soil penetration depth of 10 cm. The VWC sampling volume is an elliptical cylinder extending a 3 cm radius beyond the TDR probes, measuring approximately 825 cm^3. The sensor is attached to one end of a shaft on the TMM, while a bolt is connected to the opposite end. When the TMM moves, the wheel-driven shaft rotates in a circular fashion. As the sensor's probes enter the soil, the bolt passes by a series of magnets that triggers the data logger to take a measurement. The probes are inserted into the soil approximately every 2.5 m.

An Omega LC302-500 stainless steel compression load cell (Omega Engineering, Inc. Stamford, CT) was used to measure the insertion force (lb) of the TDR moisture sensor probes. As the probes penetrate the soil, pressure is exerted against the load cell, indicating the degree of force for penetration. A standard cone penetrometer of the ASAE (ASAE Standards, 2005) has a 9.8 mm diameter shaft with a 30° angle and a base of 12.8 mm diameter. The TMM unit differed in that the 9.8 mm diameter shaft did not have the 12.8 mm diameter tip and there were two penetrometers recorded with each reading. Data were converted to MPa and divided by one-half for comparison to single penetrometer data in the literature.

A GreenSeeker RT100 active sensor (NTech Industries, Inc. Ukiah, CA) evaluated turf canopy NDVI in the fairway, but data are not presented. A Trimble *Ag*GPS 132 receiver (Trimble Navigation Unlimited, Sunnyvale, CA) was used to compile GPS information (i.e., latitude, longitude, altitude, speed, and time) for the data. The ESRI ArcGIS GIS and mapping software, versions 9.1 and 9.2 (ArcMap and ArcScene), along with the ArcGIS Spatial Analyst and Geostatistical Analyst extensions, were used to develop, display, analyze, and interpret maps of the TMM data (ESRI, 2004a, 2004b). The VWC and penetrometer data points were displayed on the base maps and interpolated using the kriging method of interpolation via the Spatial Analyst extension with spherical models determined to be most appropriate. The lag size used was the sampling grid distance of 2.5 m and no anisotropy was evident. The ESRI ArcPad software program was used during data acquisition to track the passes of the TMM to aid in the development of a consistent sampling grid.

Several measures of dispersion, central tendency, and shape or relative position were calculated, including the mean (average), median (middle value of the ranked data set), and mode (most frequently occurring value) (McGrew and Monroe, 2000). A significant difference between these measurements usually indicates a skewed data set.

RESULTS AND DISCUSSION

Spatial mapping following spring rains bringing the soil to field capacity on 2 May 2007 resulted in PR and VWC distributions illustrated in Fig. 1a, 1b, respectively; while mapping on 2 July following a dry period demonstrated considerably different results (Fig. 1c, 1d). Based on the 2 May PR data, the fairway was divided into two PR-SSMUs representing high and low PR areas. The SSMU boundaries mirrored the soil survey soil types where: a) the low value PR-SSMU 1 was associated with the Brill silt loam and the urban land-Chetek complex (i.e. land had been disturbed) labeled as 1a; and b) the high value PR-SSMU 2 was associated with Chetek sandy loam. Using the method reported by Krum et al. (2010), fairway 2 was divided into two VWC-based SSMUs, where these SSMUs primarily reflect soil texture and organic matter content (Fig. 1b).

Descriptive statistics for the whole fairway area are presented in Table 1 for PR and VWC data on both sample dates with the PR histogram distributions illustrated in Figure 2 for both sample dates. The mean VWC on 2 May and 2 July were 32.7 and 27.6%, respectively, while the mean PR was 3.84 and 3.82 MPa. Within the low PR-SSMU and high PR-SSMU on 2 May the mean PR was 3.60 and 4.24 MPa, respectively. Common measures of data variability are standard deviation (SD) and coefficient of variability (CV), and these allow easy comparison across SSMUs and dates. Both VWC and PR variability were greater on 2 July compared to 2 May; but similar within each of the PR-based SSMUs on 2 May.

Kriging of PR and VWC for fairway 2 generated semivariograms that quantified spatial autocorrelation of the data with Figures 3a and 3b illustrating results at field capacity on 2 May (ESRI, 2004a). The range, nugget, sill, and partial sill are used to describe the spherical models of the semivariograms. The range, based on spatial autocorrelation of the data, is the distance (m) at which the model plateaus, indicating the spatially dependent portion of the semivariogram — i.e., sampling distances should be less than the range if data are to be spatial correlated for interpolation. For PR mapping, the range was 28m (Fig. 3a) and for VWC 28.9 m (Fig. 3b). The TMM sampling distances were approximately 2.5 m for PR and VWC, respectively, which were significantly less than the ranges of all semivariograms (including 2 July, not shown) verifying that the sampling scheme was sufficient. Using two cone penetrometers per sample point and then basing data on the total coupled with close sample distances may have aided in reducing spatial variability issues often reported for penetrometers (Sudduth et al., 2008).

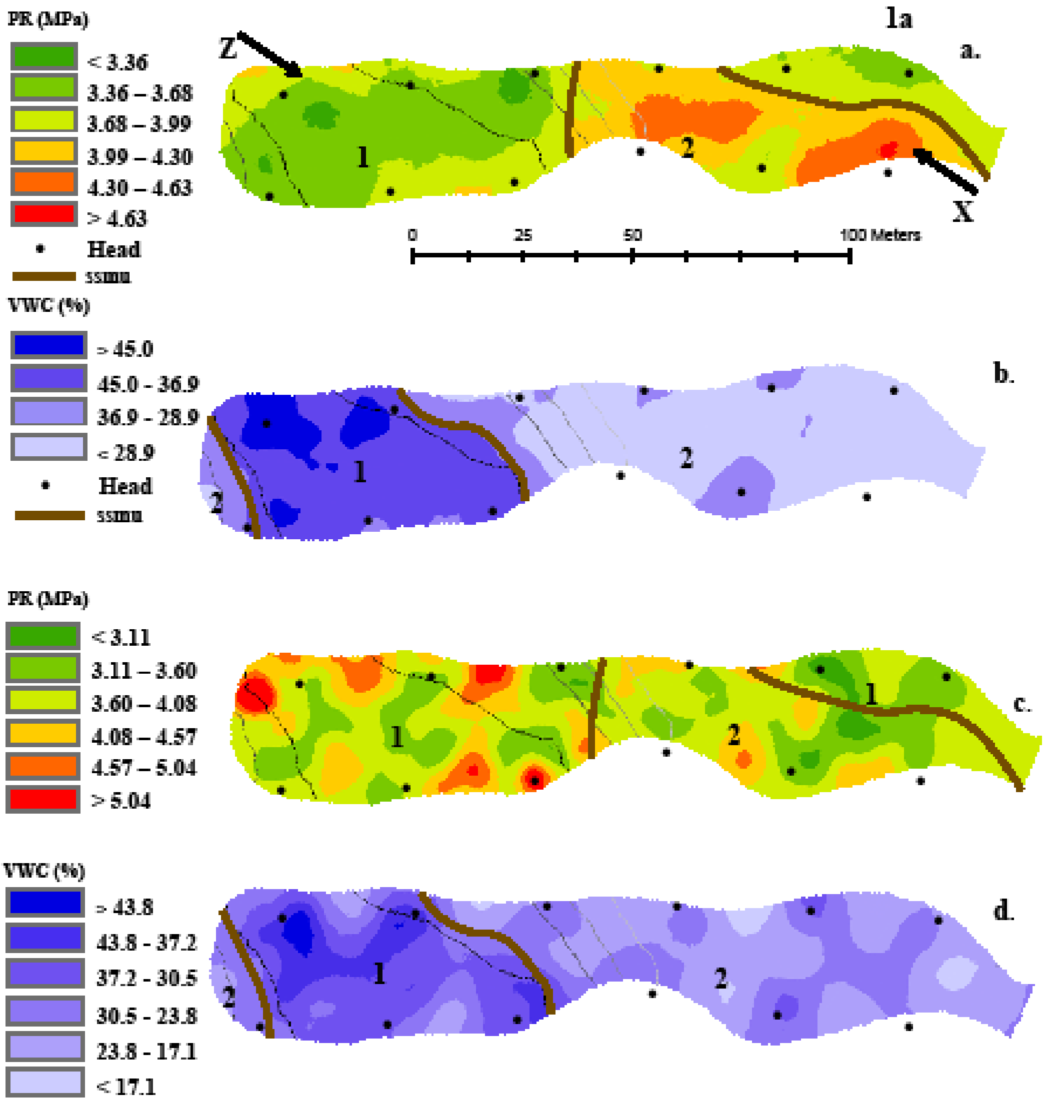

Figure 1. Penetrometer resistance (PR) and volumetric water content (VWC) and for Fairway 2 at field capacity on 2 May 2007 (a and b, respectively) and under dry conditions on 2 July, 2007 (c and d, respectively). The map legends are based on standard deviation divisions. Site-specific management units (SSMUs) for PR in a. and c. are based on 2 May 2007 PR data obtained at field capacity with low PR (1, 1a) and low PR (2) SSMUs. VWC-based SSMUs in b. and c. are based on 2 May VWC data. Elevation contours are included (lower = darker gray, higher = lighter gray). Arrows Z and X represent concentrated traffic areas.

Table 1. Descriptive statistics of volumetric water content (VWC) and penetrometer resistance (PR) for Fairway 2 on 2 May (soil at field capacity) and 2 July 2007 following a dry period where the irrigation system uniformity and scheduling influenced VWC and PR values. PR is based on single probe of 9.5 mm diameter.

Date	**Mean**	**Median**	**Mode**	**Range**	**Standard Deviation**	**CV**	**Skewness**	**Kurtosis**
% VWC								
2-May	32.7	31	27	38	8.6	26.3	0.48	-0.87
2-Jul	27.6	27	23	65	10.3	37.4	0.82	0.90
PR, MPa								
2-May	2.84	3.82	3.34	3.36	0.58	0.26	0.27	-0.2
low ssmu	3.62	3.60	3.34	2.88	0.46	0.22	0.21	0.25
high ssmu	4.20	4.24	4.24	3.16	0.58	0.23	-0.37	0.16
2-Jul	3.82	3.58	3.20	4.88	0.94	0.42	0.76	0.05

Penetration resistance is primarily affected by soil type, structure/compaction, and moisture content within a soil type (Sudduth et al., 2008). Mapping PR when the soil is at field capacity reduces the influence of soil drying within a soil type where CI has been reported to be only slightly affected by VWC decreasing from 100 to 70 % field capacity, but then PR exponentially increases with further drying (Henderson et al., 1988). However, when comparing across soil types at field capacity, higher VWC does not necessarily result in lower PR as demonstrated high VWC/low PR in the Brill silt loam area, lower VWC/high PR in the Chetek sandy loam, and then low VWC/high PR in the urban land-Chetek complex 1a SSMU (Fig. 1b). Thus, mapping at field capacity appears to reflect inherent PR of existing soil types. The VWC based SSMU delineations assist in interpretation of PR results relative to soil type areas The effects of traffic that is evenly spread over the whole area, such as mowing, and how that traffic may induce soil compaction on each soil type would be reflected in the PR map results within each soil type.

Additionally, concentrated traffic areas should be revealed where PR should be above the background PR for the particular soil type area. The upper left (arrow Z) of in fairway 1 PR map at field capacity (Fig. 1a) suggests a possible traffic influence since most golf carts enter the fairway at this site. Also, most carts exit the fairway near the green at arrow X which may contribute to the high PR at this location.

A practical means to use PR mapping at field capacity may be to set a PR limit and cultivate more often on areas exhibiting PR above the limit, regardless of

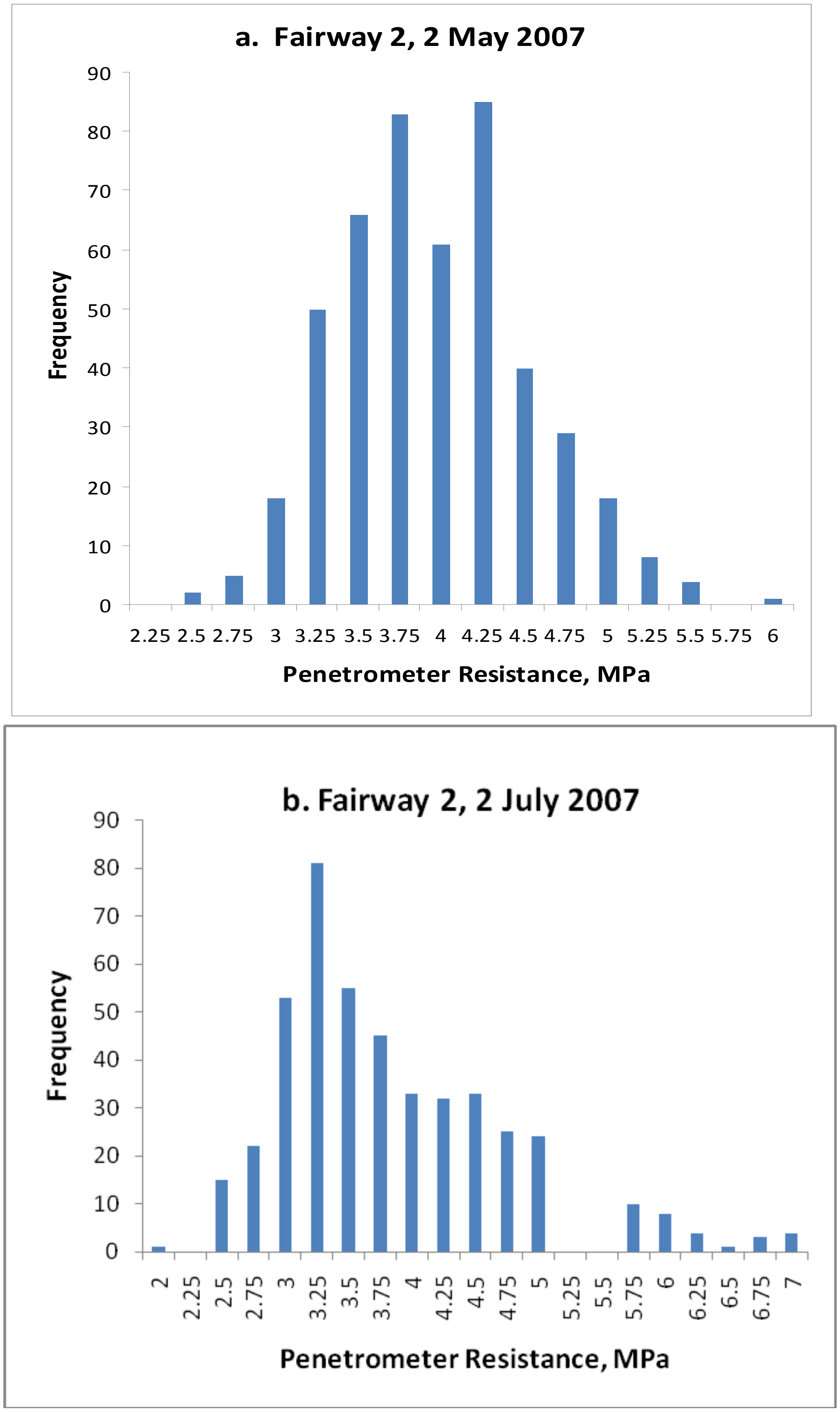

Figure 2. Histogram of Fairway 2 penetrometer resistance (PR) data on 2 May (field capacity) and 2 July 2007 (dry period). PR is based on a single 9.5 mm diameter cone penetrometer – i.e. total of the dual penetrometer configuration penetrometer resistance data in the field would be twice the single probe value.

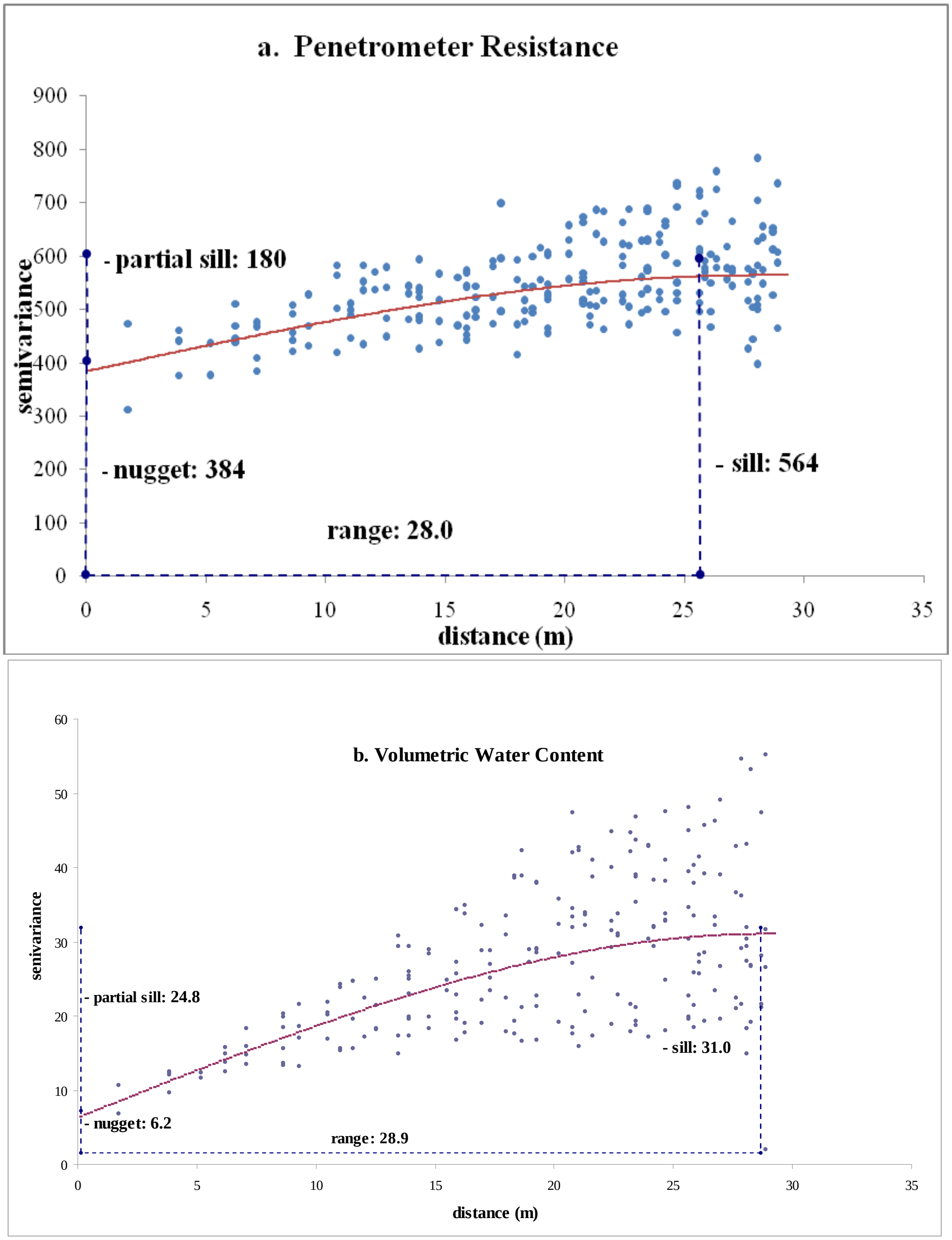

Figure 3. Semivarograms for penetrometer resistance (units is lbs per inch^2 force where 1.0 MPA = 145 psi) (a) and volumetric water content (b) for Fairway 2 in May 2007 from mapping at field capacity.

whether the high PR is related to inherent soil type of traffic patterns. Since grasses (barley and wheat) have been reported to tolerate higher PR in terms of limiting root growth, areas with PR > 3.99 MPa may be set at sites requiring more frequent cultivation. The limit for PR to trigger cultivation could be adjusted on the site based on turf manager experience.

If the PR >3.99 MPa base was used for fairway 1, then only about 40 % of the fairway area would require cultivation on a more frequent basis (Fig. 1a). Since the PR spatial maps denote the locations with the highest PR values, it may be possible for the turfgrass manager to periodically monitor these specific locations for guidance in cultivation timing; taking care that mapping was at field capacity conditions. This would require the availability of a hand-held penetrometer unit or a mobile unit.

As noted, within a soil type as the soil dries below field capacity, PR increases, especially at below 70 % field capacity (Henderson et al., 1988; Unger and Kasper, 1994). The relationship between PR and VWC is the prime reason for research scientist interest in dual function sensors that can quantify both characteristics (Hemmart and Adamchuk, 2008). A comparison of the PR spatial maps (Fig. 1a, 1c) and associated VWC maps (Fig. 1b, 1d) reveal substantial differences in PR and VWC spatial patterns from 2 May (field capacity) to 2 July (dry period). The high PR areas in both PR-SSMU 1 and 2 often occur in between irrigation heads where the VWC is lower.

The 2 May mapping showed no areas of < 18% VWC but on 2 July a number of sample points were at <18% VWC (Fig. 4a, 4b). Also, the areas denoted by arrows X and Z in Figure 1a that appeared to be related to concentrated traffic patterns were even more pronounced in the 2 July period (Fig. 1c). Regression relationships of PR versus VWC demonstrated higher correlation coefficients on 2 July compared to 2 May. These results indicate that spatial mapping for PR during drier periods for the purposes of site-specific cultivation would be misleading. However, spatial mapping of PR and VWC on an athletic field or horse racing venue during drier periods to identify high PR and PR-VWC relationships for purposes of performance testing related to player or horse safety and playability for the sport would be very useful (Carrow et al., 2010).

In conclusion, this paper illustrates the feasibility of spatial mapping of PR and VWC to identify high PR areas for site-specific cultivation. However, for the purpose of site-specific cultivation, the results demonstrate the necessity of mapping at field capacity to remove high PR locations due to soil drying substantially below field capacity VWC. Site-specific cultivation areas or SSMUs could be based on setting a high PR limit that is expected to adversely affect rooting, infiltration, or plant performance and this limit could be adjusted based on experience. In this study, the areas with high PR at field capacity were associated with specific soil types and smaller areas of localized traffic.

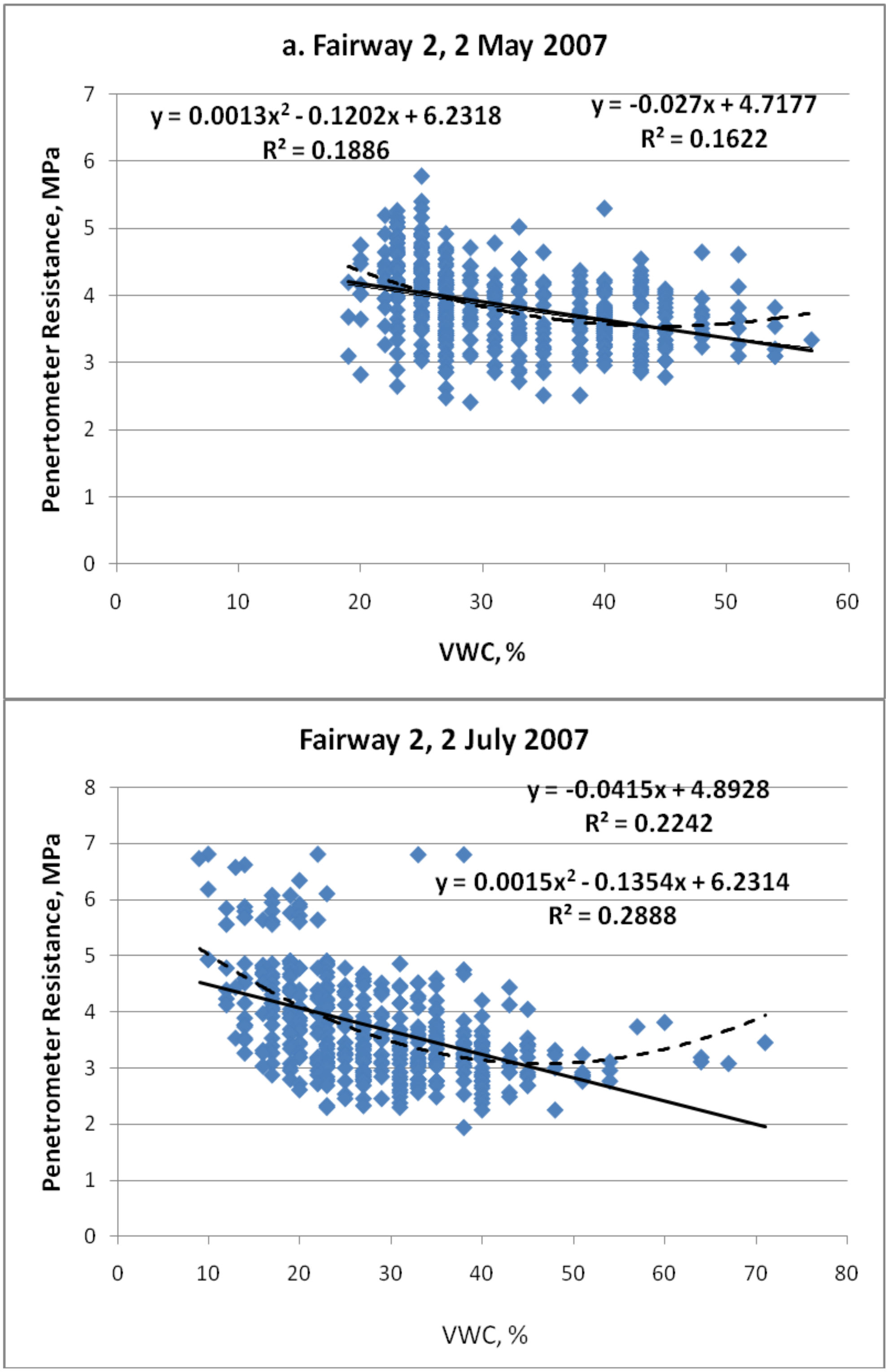

Figure 4. Relationship between penetrometer resistance (PR) and VWC on Fairway 2 when the soil was at field capacity on 2 May 2007 and during a dry period in 2 July 2007.

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