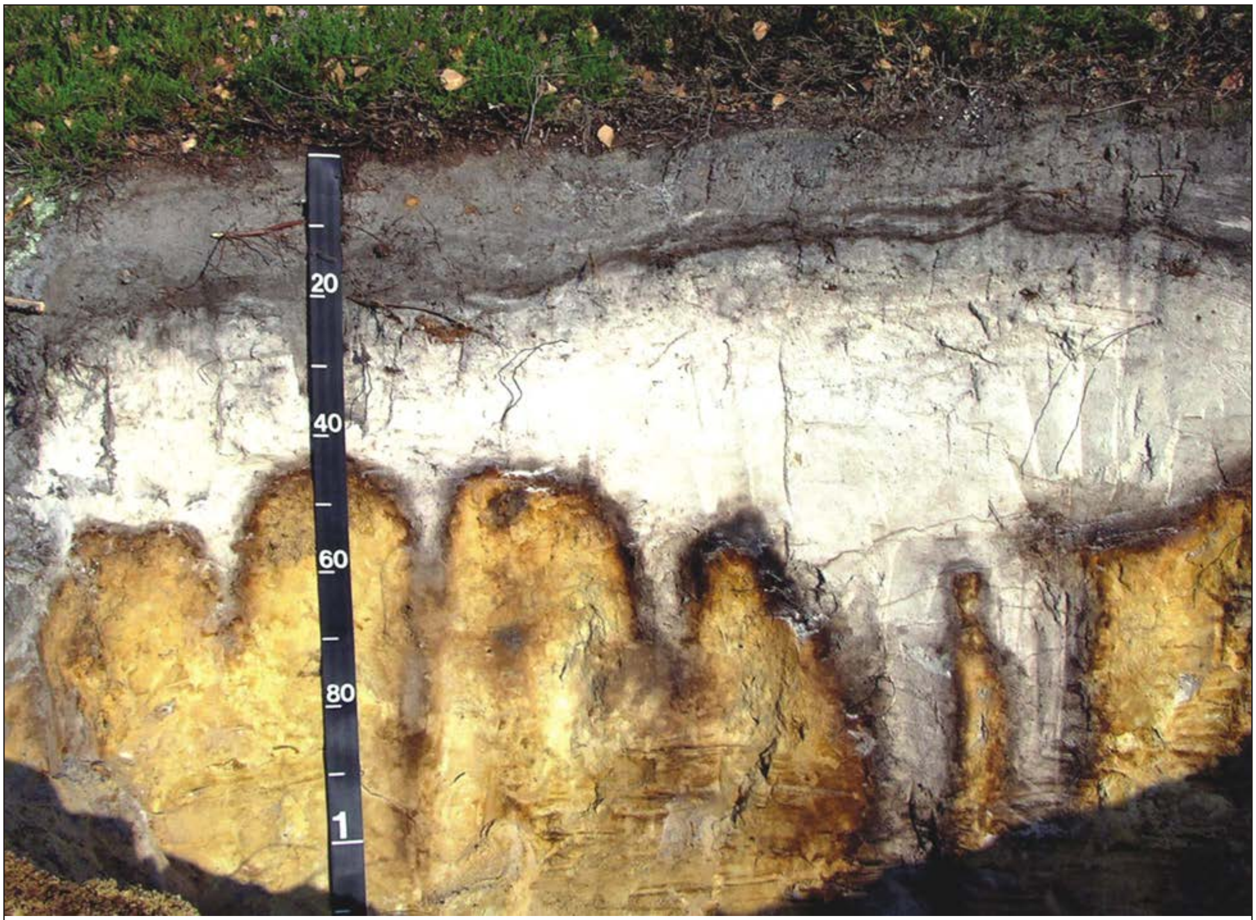

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Spatial Patterns of Penetration Resistance and Soil Moisture Distribution in a Sandy Loam Soil (*Eutric leptosol*)

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ABSTRACT

Bivariate relations between penetration resistance and soil moisture content was conducted on sandy loam soil (*Eutric leptosol*) at the University of Juba demonstration farm. Soil Penetration Resistance (PR) was measured using an Eijkelkamp pocket penetrometer to a depth of 0-15 cm depth with Soil Moisture Content (SMC) measured using an Eijkelkamp sensor theta probe. Measured SMC within the plots varied from 9-35% whereas, the PR varied from 0.1 to 4.5 kg cm^{-2}. The results showed significant negative correlation between PR and SMC expressed by a polynomial function with r^2 = 0.48 and Pearson Coefficient, R = -0.657. Spatial distribution of PR and SMC using both kriging and Inverse Distance Weighting (IDW) interpolation methods showed no significant differences. However, PR tended to decrease with an increasing SMC in an easterly direction. The results also showed that the spherical model gave the best fit for both PR and SMC at r^2 = 0.527 and 0.747 with moderate and strong spatial dependency at 28.9 and 10.53%, respectively. Though the effective range A_0, for both PR and SMC at 24.14 and 30.4 m, respectively were more or less similar, the strong spatial dependency of SMC suggested its significance as a limiting factor for plant growth as opposed to PR which on average was at 1.592 kg cm^{-2}.

Key words: Kriging, Inverse Distance Weighting (IDW), polynomial function, soil moisture content, penetration resistance

INTRODUCTION

Penetration resistance is a spatio-temporal soil attribute that is strongly influenced by several variables whether as single or multiple with each interacting variables, e.g., SMC (θ), bulk density (ρ_b), matric suction (ψ), organic matter, soil texture and structure. Often, assessing the spatial and temporal variations of PR would require identifying and quantifying which single or multiple variables interact with each other to produce the resultant PR value. In one study on Brazilian oxisols (Vaz *et al*., 2011) derived exponential equations between corrected PR values and θ or ψ and ρ_b. They further argue that, PR variations could be reduced if the θ and ρ_b were normalized and expressed as relative values. Whereas the soil of the study area exhibited a more or less homogenous texture, any spatial variations of the PR is predominantly a function of variations in θ and ρ_b. Indeed, soil bulk density at any given θ, would be the single major variable whose spatial variations would influence the PR. In agricultural soils, PR has been widely studied and recognized as one major limiting factor on root development (Lambers *et al*., 2007; Bengough, 2003;

Lipiec *et al*., 2003) and hence reduced plant growth potential (Vermeulen *et al*., 2010), between 5-15% reduction in yield of oats (Heinonen *et al*., 2002) and on yield of e.g. corn (Tracy and Zhang, 2008; Konopka *et al*., 2008); on wheat crop performance (Latif *et al*., 2008) on seed emergence rate and growth establishment of cow pea (Lomeling and Abass, 2014). Similarly, increased soil compaction led to decreased emergence of soybean seedlings (Hyatt *et al*., 2007) as well as of coffee plant seedlings (Masaka and Khumbula, 2007; La *et al*., 2013; Reintam *et al*., 2005) found out that depending on the degree of fertilization, the assimilation of both nitrogen and potassium in spring barley plants decreased by up to 37% as result of high bulk density. Conversely, Altikat and Celik (2011) reported that increased soil compaction led to increased cone index which in turn led to increased seed-soil-contact of red lentils seedlings in tilled soil.

Penetration resistance therefore, is a measure of soil compaction. It is both a qualitative and quantitative attribute that is manifested by a soil´s intrinsic ability or strength to resist penetration, deformation or displacement upon subjection to an external mechanical force prior to surpassing the threshold value. At a post threshold value, intra- or inter-aggregate cohesive forces will have been overcome often resulting into irreversible changes within the soil matrix that is then evident as compaction.

Soil compaction is predominantly influenced by the amount of soil moisture content as well as magnitude of external mechanical load acting on the soil matrix during tillage operations (Defossez *et al*., 2003). It is also dependent on soil texture (Hamza and Anderson, 2005). In sandy loam soil (*Eutric leptosol*) it was also found out that higher cone index values and therefore, penetration resistance was contingent on critical amounts of both silt and clay components. Cone index therefore, tended to increase with decreasing silt and clay contents (Lomeling, 2013).

Vehicular compaction of soil beyond some threshold value can lead to over-consolidation of soil with irreversibly reduced pore size distribution especially in the subsoil (Lipiec *et al*., 2012). Tillage operations are often conducted on compacted soils to enhance optimum root distribution and therefore nutrient uptake. This can be a very expensive undertaking especially in terms of fuel costs (Lavoie *et al*., 1991). In terms of dual or bimodal pore systems, soil compaction has differentiated impacts on the pore geometry and continuity. Predominantly horizontal as well as inter-aggregate rather than vertical pores are more prone to change during deformation and shearing of soil aggregates upon subjection to external mechanical force (Schaffer *et al*., 2007, 2008).

Although several studies have shown that PR is negatively correlated to soil moisture content, such a relationship would be less meaningful if it did not integrate the significance of normalized bulk density, especially where no measurements on bulk densities were conducted. Significance of the bulk density variations across the measured plots could only be inferred from PR-θ mathematical functions. Against this background, we hypothesize that expressing the PR as function of normalized bulk density at given θ would provide better understanding on the significance of bulk density. Spatial variability of soil penetration resistance as measured by cone index can be visualized by maps generated by kriging and Inverse Distance Weighting (IDW) interpolation methods (Lomeling, 2014; Lomeling and Abass, 2014). The generated maps help in spatially delineating and localizing zones as affected by tillage, wheel traffic and traction and provide extra information in formulating best management practices especially in precision agriculture. Several researchers have attempted map soil compaction (Domsch *et al*., 2006).

The main objective of this study was to assess and characterize spatial patterns and explain the significance of normalized bulk density on PR-SMC relationship.

MATERIALS AND METHODS

Soil studied: The study was conducted between June and October 2014 at the demonstration and research farm of the Department of Agricultural Sciences, CNRES, University of Juba, South Sudan. The soil is classified as sandy loam soil and according to FAO-90 as comprising of predominantly *Eutric leptosol* with associated *Eutric leptosol* (Harmonized World Soil Data Viewer 1.2) (Table 1).

This area lies within the Greenbelt agro-ecological zone characterized by wet tropical climate during the rainy months from April to November with daily temperatures of about 28°C. The average annual rainfall is about 650 mm. From December to March is the dry climate with no rainfall. Average daily temperatures during this period are about 39°C. Both SMC and PR were conducted on 55 geo-referenced points chosen from 11 out of 32 randomly selected plots each 10×10 m. In each single plot and at a distance not less than 1 m from the next successive point, 5 geo-referenced points were selected and the SMC and PR measured (Fig. 1).

Normalized bulk density: Several mathematical functions for expressing the PR-θ relationship were tested a priori and the one that gave the highest r^2, was chosen. In that regard, the polynomial function was chosen because it gave better expressed the relationship between PR and θ. The value of the constant in the polynomial function was 1.49 g cm^{-3} and was closer to the measured soil bulk density of 1.34 g cm^{-3}. Minimum and maximum normalized bulk density values were calculated to include a whole range of bulk densities from as low as 1.09 to as high as

Table 1: Average values of some of the physical and chemical properties of sandy loam soil (*Eutric leptosol*)

Soil physical and chemical features	Description
Soil Mapping Unit (SMU)*	Eutric Leptosol
USDA Texture Classification*	Sandy loam
Drainage Class (0-0-5%)*	Moderately well
Sand (%)	47.6
Silt (%)	45.1
Clay (%)	7.3
pH (LaMotte STH Test Method)	7.2
Vol. water content (%)	10.4
Bulk density (g cm^{-3})	1.34
Humus content (%)	2.95
Organic carbon content (%)	0.72

*Harmonized World Soil Data (HWSD) Viewer 1.2

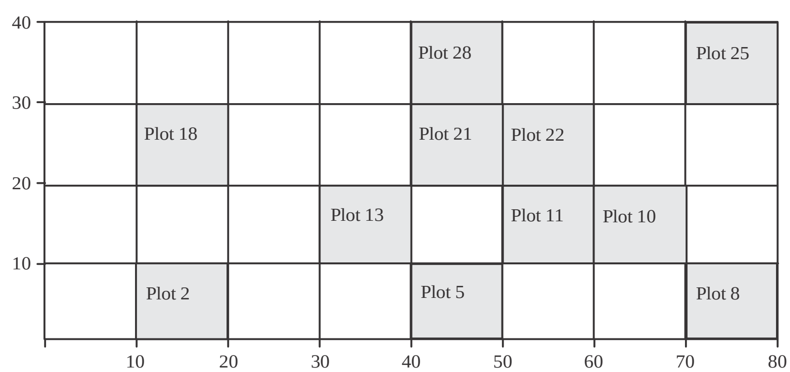

Fig. 1: Diagrammatic outlay of plots selected for random sampling at the research and demonstration farm, University of Juba

1.89 g cm^{-3} which would cover the whole range of expected values from extremely loose to highly compacted soils with correspondingly low to high PR respectively.

Soil textural composition was conducted by extruding samples using labelled aluminum cans of diameter 2 cm and height 1.5 cm from similar geo-referenced points where the PR and SMC measurements were carried out.

The SMC was measured at each point using a 4 pin Soil Moisture Sensor Theta Probe (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) with measuring range 5-55% of volume percentage soil and mounted on an Eijkelkamp penetrologger. The SMC was read out in vol. %. Subsequently, the PR measurements were done on the same selected points initially for SMC and measured using an Eijkelkamp pocket penetrometer in kg cm^{-2}. Both measured SMC and PR data were then used as input data for generating contour maps and spatial distribution of both variables using the geo-statistical software GS+^{TM} Version 9 (Gamma Design Software, LLC, Plainwell Michigan, USA). Isotropic semi-variograms and model parameters for both SMC and PR were established to assess the nugget, sill, effective range as well as spatial dependency.

Geo-statistical mapping: Geo-statistical software GS+^{TM} Version 9 (Gamma Design Software, LLC, Plainwell Michigan, USA) was used to quantify the isotropic spatial variability as well as construct semi-variogram models for the soil cone index. Various models were tested during each simulation run and the spherical model was selected as the best fitting model based on the values of weighted Residual Sums of Squares (RSS), regression coefficient (r^2) and relative spatial structure indicator (Nugget/Sill) that indicated the spatial dependency.

The spherical isotropic model:

$$\gamma(h) = C_0 + C\,[1.5\,(h/A_0) - 0.5\,(h/A_0)^3] \text{ for } h \leq A_0 \quad (1)$$

$$\gamma(h) = C_0 + C \text{ for } h > A_0 \quad (2)$$

Where:

γ (h) = Semi-variance for interval distance class h
h = Lag distance interval
C_0 = Nugget variance$\geq$0
C = Structural variance$\geq C_0$
A_0 = Range parameter

Interpolation was performed using both the ordinary kriging and the Inverse Distance Weighting (IDW) methods. The spatial trend of SMC and PR distribution was visualized from contour maps. Different classes of spatial dependence for the soil variables were evaluated as the ratio of the nugget to sill. For ratio $0 \leq x \leq 25$ the variable is considered to be strongly spatially dependent, for ratio $25 \leq x \leq 75$ moderately spatially dependent and >75 weakly spatially dependent.

RESULTS AND DISCUSSION

The results of spatial distribution of SMC using both IDW and kriging interpolation methods is shown as in Fig. 2 and 3. High SMC values between 29-35% were predominant at the left hand corner (0-30 m Eastings and 0-34 m Northings) especially in the plots 1, 2, 3 14 to 18. Moreover,

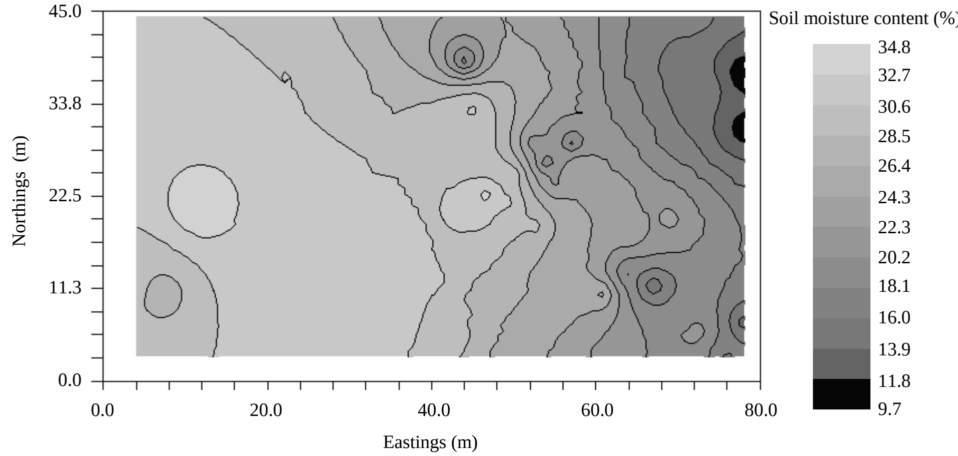

Fig. 2: Contour map of soil moisture distribution using the IDW method of a *Eutric leptosol*

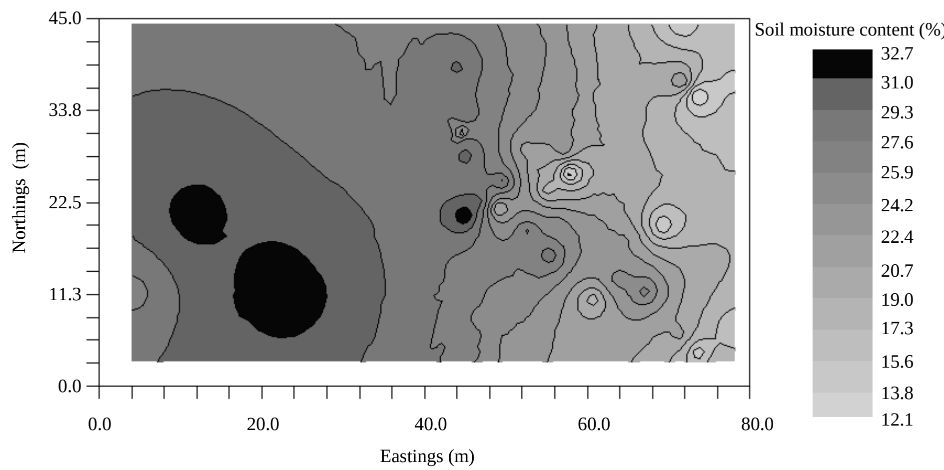

Fig. 3: Contour map of soil moisture distribution using the kriging method of a *Eutric leptosol*

moderate SMC values between 14-26% were predominant at the center especially in the plots 5, 10, 11, 13, 21, 22 and 28 and comparatively low SMC values between 10 and 12% were measured at the extreme right-hand corner of the farm especially in the plots 8, 9, 23 and 25. The IDW generated contour maps showed that there was a general decrease in the SMC in an easterly direction. For such a *Eutric leptosol*, which exhibits more or less similar structural and textural homogeneity, this unusual spatial distribution of SMC could be attributed to relatively high bulk density leading to poor drainage of soil moisture within the left half of the demonstration farm. In the absence of cultivated farm crops, evapotranspiration is reduced and much of the soil moisture was retained for longer periods. On the contrary, low SMC values at the right half of the farm indicated intense soil moisture uptake and evapotranspiration by the many fruit (guava, mango) and forest (eucalyptus, ebony) trees.

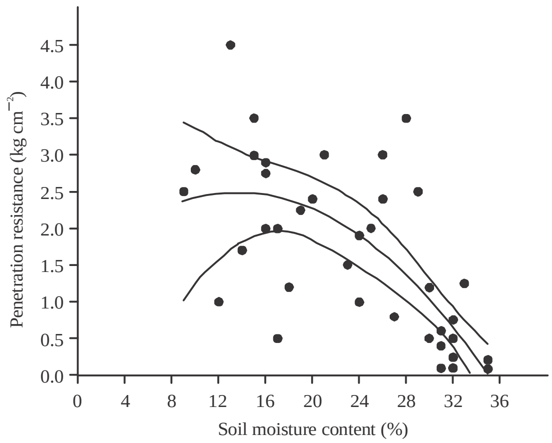

Fig. 4: Relationship between PR and soil moisture content expressed by a polynomial function at 95% confidence interval (blue lines)

Table 2: Mathematical functions of penetration resistance with regression coefficients

Equations	Functions	Regression coefficients
$PR = 10.601exp^{-0.097x}$	Exponential	$r^2 = 0.4622$
$PR = -0.0993x+3.9702$	Linear	$r^2 = 0.4313$
$PR = -1.947ln(x)+7.6547$	Logarithmic	$r^2 = 0.3809$
$PR = -0.0054x^2+0.1473x+1.4885$	Polynomial	$r^2 = 0.4791$
$PR = 336.87x^{-1.857}$	Power	$r^2 = 0.3889$

Figure 4 shows a negative correlation between the PR and SMC at $r^2 = 0.48$. At SMC between 10-25%, most PR values were widely spread between 1 and 3 kg cm^{-2}. Unusually high PR at low SMC would suggest the presence of hard pans, heavily trampled zones or plant roots during measurements. The PR values tended to congregate between 0.1 and 1.5 kg cm^{-2} at SMC 26-35%.

The correlation coefficients between PR, θ and the soil textural components are shown in Table 2. Both sand and clay components positively correlated with PR, whereas silt and θ were negatively correlated. Similarly, θ negatively correlated with both sand and clay but positively correlated with silt. As between PR and θ, any increase in the latter showed a decrease of the former. Similar results of PR-θ negative correlations was also reported by Veronese *et al.* (2006) and Van Quang *et al.* (2012).

The positive correlation between PR both with sand and clay components at soil moisture values less than the field capacity would suggest the presence of larger pore spaces in a drier unsaturated soil. However, an increase in both components enhanced further increase in the degree of particle interlocking and therefore increased frictional resistance at the contact points. Equally, the PR negatively correlated with silt component indicating a decrease in PR with subsequent increase in amount of silt. Similar results by Baziar and Ziaie-Moayed (2006) reported that soils with high percent of silt of between 30-50% showed moderate decrease of the cone tip resistance than those between 0-30%. At lower contents of silt and in the presence of the larger and coarser predominating sand particles, the soil would behave more or less like a sandy soil with high article interlocking and high frictional resistance. With increased silt content during loading sequence, the finer and smaller silt particles would move to occupy much of the void space and be surrounded by soil moisture. Especially under increased θ or saturated conditions this would lead to increased pore water pressure significantly reducing the inter-particle contact and also reduced penetration resistance as shown by the negative correlation between θ and silt in Table 3.

Table 3: Correlation coefficients between penetration resistance, soil moisture and soil textural components

Correlation parameters	PR	SMC (θ)	Sand	Clay	Silt
PR	1	-0.0993	0.0061	0.1039	-0.0239
SMC (θ)		1	-0.1162	-0.3650	0.1634
Sand			1	-0.0581	-0.8304
Clay				1	-0.1696
Silt					1

PR: Penetration resistance, SMC: Soil moisture content

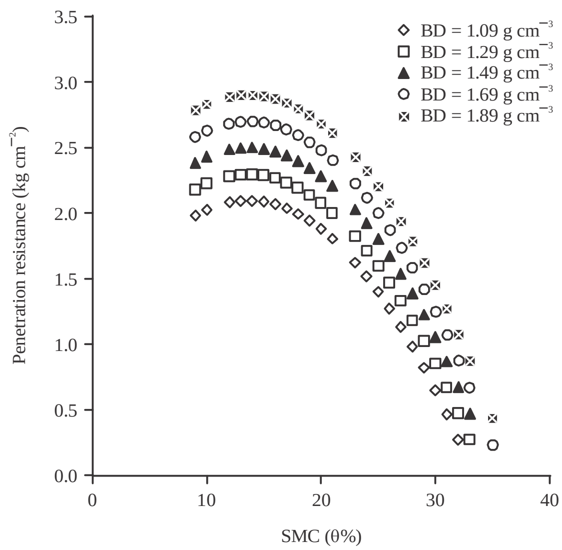

Fig. 5: Measured penetration resistance as a function of soil moisture content for different normalized soil bulk (ρ^N_b) densities of a *Eutric leptosol*

Substantially higher values of the penetration resistance were found, especially when soil moisture was between 10-20% for all normalized bulk densities as in Fig. 5. The relationship showed similar patterns of PR with θ at the different normalized bulk densities, notably a polynomial decomposition of PR with θ.

The PR variations at low θ values between 10-20% were large between 2-3 kg cm^{-2}. The PR variations become lesser as PR decreased to between 0.5-1.5 kg cm^{-2} at high θ values between 30-36%. Because the measured plots showed spatial variability in soil texture, changes in soil texture had by inference significant influence on both SMC and PR. Lomeling (2013) while working on *Eutric leptosol* found that spatial variations of the different soil fractions showed differentiated patterns with maximum values of the sand fraction (52-65%) predominantly at the extreme left hand corner of the demonstration farm (Fig. 6). The PR varied as a function of soil texture and it negatively correlated with increase in sand content, whereas this positively correlated with increase of both silt and clay contents in an easterly direction. The silt fraction appeared to influence the spatial structure of PR.

At high silt content with correspondingly high SMC, the soil showed low PR values. This can be attributed to increasing role of inter-granular water content that tended to lower inter-granular contacts with a corresponding reduction in frictional forces. With pores de-saturating, the soil became drier with more loss of inter-granular water leading to subsequent increase in frictional forces. In most cases, fine and dry sand tended to behave more like silt significantly influencing the

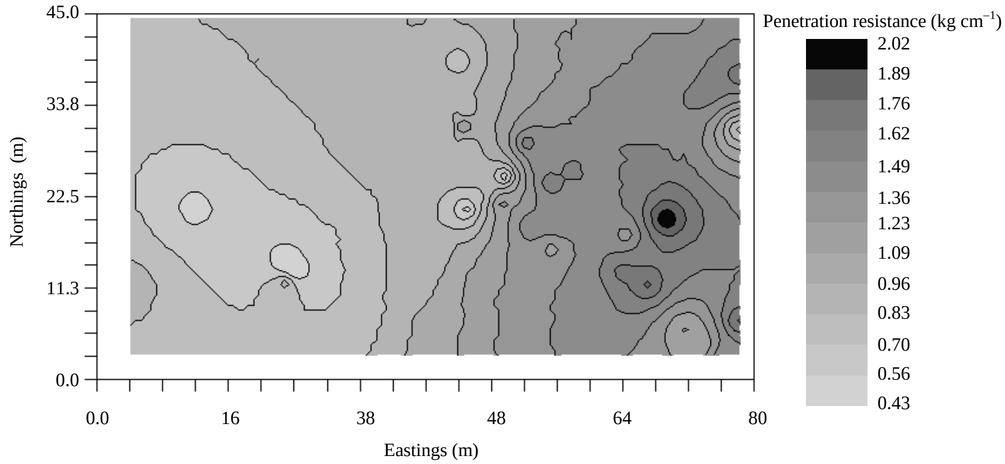

Fig. 6: Contour maps of soil penetration resistance using the kriging method for a *Eutric leptosol*

Table 4: Statistical moments of penetration resistance and soil moisture content of a sandy loam soil (n = 45)

Variables	Mean	Standard deviation	Variance	Kurtosis	Skewness
PR (kg cm^{-2})	1.591	1.158	1.376	-0.760	0.441
SMC (%)	23.95	7.658	60.151	-1.276	-0.322

PR: Penetration resistance, SMC: Soil moisture content

PR. Therefore, measured under both wet and dry conditions and where frictional forces are either low or high, this has great significance in understanding soil-water-interactions in crop production, supporting the idea of conducting PR measurements between 0.3 and 3.0 kg cm^{-2}. From Fig. 5, it is evident that the normalized bulk density values (ρ^N_b) allows a better comparison of PR measurements obtained for wide range of variations in bulk density under different SMC conditions. For example, PR values for wet soil at 15% SMC was 2 kg cm^{-2} at 1.09 g cm^{-3} bulk density while, this at similar SMC was 3 kg cm^{-2} at 1.89 g cm^{-3} bulk density (Table 4). Our results on the negative correlation between PR and SMC at the different bulk densities concur with those reported by Seker (1999), Vaz *et al.* (2001), Aksakal *et al.* (2010) and Aksakal and Oztas (2010). Similar findings on uncultivated red dermosol (clay loam) and brown sodosol (sandy loam) from coastal lowlands of South-East Queensland were also reported by Costantini (1996). The results showed that at some given SMC, the PR decreased with decreasing bulk density. This however, was the contrary for blade-cultivated red dermosol (clay loam) and red kandasol (sandy clay loam) where at some given SMC, the PR decreased with increasing bulk density.

Isotropic semi-variogram for PR in Fig. 7 showed moderate spatial dependency at 28.9% with an effective range A_0 at 24.14 m. Such moderate spatial dependency and comparatively shorter A_0 or separation distance of PR would suggest the significance of previous anthropological activities that may have influenced the PR. The SMC whereas showed a very strong spatial dependency at 10.53% with effective range A_0 at 30.4 m (Fig. 8). It should be noted, that there were no significant differences in the range values of both PR and SMC. However, the strong spatial dependency of SMC would suggest the significant role of SMC as opposed to PR in influencing plant growth within the demonstration farm. Spatial distribution of SMC was more influenced by lithogenic factors, whereas that of the PR was more anthropological.

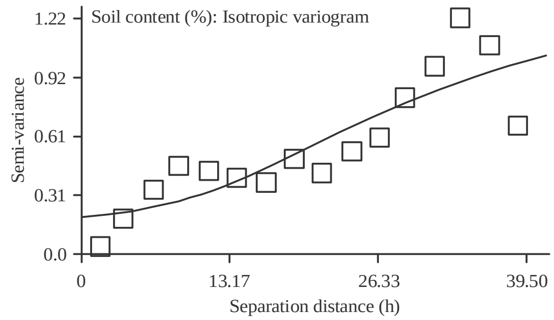

Fig. 7: Curve fitting between separation distance and semi-variance using the spherical model (C_0 = 0.2000, C_0+C = 1.900, A_0 = 30.40, r^2 = 0.747, RSS = 0.392)

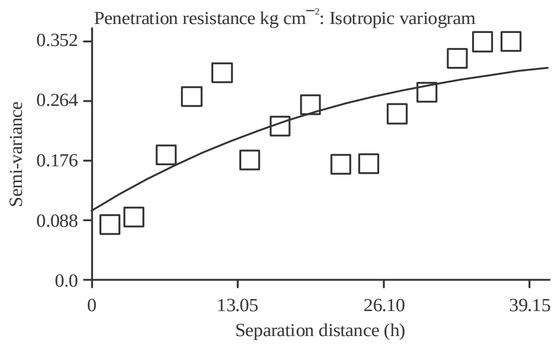

Fig. 8: Curve fitting between separation distance and semi-variance using the spherical model (C_0 = 0.1000, C_0+C = 0.346, A_0 = 24.14, r^2 = 0.527, RSS = 0.0482)

Table 5: Geo-statistical parameters from spherical model of both penetration resistance and soil moisture content of a loamy sand soil (*Eutric leptosol*)

Parameters	PR	SMC (θ)
Nugget, C_0	0.1000	0.2000
Sill, C_0+C	0.346	1.900
Range, A_0 (m)	24.14	30.40
RSS	0.0482	0.392
Regression coefficient (r^2)	0.527	0.747
Spatial dependency	0.289	0.1053
(Nugget/Sill)	(28.9%)**	(10.53%)***

Spatial dependency: 0-25%*** strong, 25-75%** moderate and >75%* weak, PR: Penetration resistance, SMC: Soil moisture content

The prevailing PR measured during the study varied between 0.5-4.5 kg cm^{-2} (the equivalent of 50-450 kPa, i.e., 1 kg cm^{-2} is approximately 100 kPa). Root growth may be impeded and consequently crop yield reduced if the increasing penetration resistance exceeded the threshold value of about 2,000 kPa (or 2 MPa). The measured penetration resistance was therefore considerably lower than that of threshold value and so no negative impacts on root growth and subsequently crop yield would be expected.

Table 5 shows some geo-statistical parameters for both PR and SMC with moderate (28.9%) and strong (10.53%) spatial dependency respectively. A comparatively larger range value A_0 at 30.4 m for SMC indicated that this soil variable had a more limiting effect than the PR with A_0 at 24.14 m. However, both soil variables exhibited consistent spatial patterns with SMC decreasing and PR increasing concurrently in a similar direction. Consistent spatial patterns of both soil variables would indicate the possibility of developing effective, site-specific soil tillage strategies and practices for the University of Juba demonstration farm. We can assume therefore, that prospects for precise soil management increases as the degree of spatial dependence of both SMC and PR increases. Conversely, precision soil management practices would be more difficult, if spatial distribution of both variables showed wide ranging spatial dependencies between them, i.e. one weak the other strong.

CONCLUSION

Soil PR measurements that were conducted on eleven randomly chosen plots of a sandy loam soil (*Eutric leptosol*) at the University of Juba research and demonstration farm showed considerable variations with respect to SMC (θ) and bulk density (ρ_b). Relationship between the PR and SMC was adequately expressed by a polynomial function. However, the expected relationship between PR and bulk density at the different SMCs was simply inferred through the normalization process. The normalized soil bulk density proved to be a very useful parameter in assessing its variability effects on SMC and PR which further helped better explain the influence and significance of bulk density and SMC on PR responses. The PR tended to better correlate with SMC at higher SMC values than at lower ones partly due to increased effects of soil water pressure that tended to homogenize PR.

In conclusion, the spatial patterns of PR and SMC showed no significant compaction effects within the demonstration farm even at maximum PR value of 5 kg cm^{-2} (or 0.5 MPa). The PR values were generally low and would not affect root growth and subsequently crop yield. Generally, both geo-statistical interpolation methods: IDW and kriging proved to be efficient tools for characterizing spatial patterns of PR and SMC and thus, provided useful information for effective soil management practices in precision agriculture. Further research on a macro scale should focus on describing PR-SMC patterns in Central Equatorial State (CES) of South Sudan where the *Eutric leptosol* accounts for much of the soil group.

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