Bulgarian Journal of Agricultural Science, 19 (No 2) 2013, 248-254
Agricultural Academy

SPATIAL VARIABILITY OF SOIL PENETRABILITY AND DISTRIBUTION OF COMPACTION LAYER AS AFFECTED BY LONG-TERM PLOUGHING AT SHALLOW DEPTH IN RAMBUDA IRRIGATION SCHEME IN VHEMBE DISTRICT, SOUTH AFRICA

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Abstract

NETHONONDA, L. O., J. J. O. ODHIAMBO and D. G. PATERSON, 2013. Spatial variability of soil penetrability and distribution of compaction layer as affected by long-term ploughing at shallow depth in Rambuda irrigation scheme in Vhembe District, South Africa. *Bulg. J. Agric. Sci.,* 19: 248-254

The objective of the study was to determine the soil penetrability and distribution of compacted layer as affected by long-term shallow ploughing in Rambuda irrigation scheme. Soil penetrability measurements were made at each node of a 100 m grid using a static electronic penetrometer fitted with an integrated GPS and data logger system. A 130 mm cone was inserted into the soil at 25 mm intervals from 0-750 mm depth at a minimum insertion speed of 0.2 m/min and a maximum speed of 2 m/min. Measurements of cone penetrometer were done when the soil was at field moisture capacity. Data were subjected to descriptive statistical and geostatistical analysis. A compacted layer was detected below 250 mm depth. The coefficient of variation for the topsoil (36%) and subsoil (21%) exhibited moderate variation. Spherical and exponential models were best fit for the semivariogram analysis. Soils displayed a high spatial distribution of compacted layer particularly in the topsoil horizons. Cone penetrometer resistance for the topsoil was generally low to medium but very high for the subsoil varying from 2553 to >3010 kPa indicating that the subsoil is strongly compacted due to continuous shallow tillage. The values were higher than threshold values for root elongation for most crops.

Key words: Spatial variability, soil penetrability, cone penetrometer resistance, semivariograms, compacted layer, Rambuda irrigation scheme

Introduction

Anthropogenic activities such as tillage and movement of vehicles are major causes of compacted layer across the agricultural fields (Taylor and Brar, 1991; Kílíç et al., 2005). A compacted layer limits nutrient uptake, water infiltration and redistribution, aeration, seedling emergence and root development, resulting in decreased yields, increased erosion potential and difficulty in soil cultivation (Bennie and Laker, 1975; Bennie and Krynauw, 1985; Taylor and Brar, 1991; Bengough et al., 2011). Soil is more susceptible to compaction under annual cropping due to continuous shallow depth tillage (Júnior et al., 2006) while Kílíç et al., (2005) reported that continuous moldboard tillage at the same depth densifies the soil resulting in the formation of a plough pan below the tillage depth. Soils are differently susceptible to compaction as influenced by soil texture (Ben-

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nie and Krynauw, 1985). Studies that were conducted in South Africa have shown that soils with clay content <15% in the tilled layer are very susceptible to soil compaction (Bennie and Krynauw, 1985; Mallet et al., 1985; Bennie, 2003).

A soil compacted layer does not occur uniformly at the same depth across the field but, varies over the field (Mohawesh et al., 2008). Studies have found that depth and strength of compacted layer (hardpan) varies greatly from field to field and within the field (Taylor and Brar, 1991; Raper et al., 2005). It is difficult to detect compacted layer with naked eyes (Batey and McKenzie, 2006) and recently penetrometers have become very useful tools to detect soil compaction (Kees, 2005; Raper et al., 2005; Rooney et al., 2005; Batey, 2009; Bengough et al., 2011). The penetrometer mimics root penetration into the soil except that a plant root is alive and can change direction upon coming across an impediment. Studies have shown that root penetration decreases linearly with penetration resistance and roots of most plants are inhibited at 1500 kPa while roots of many plants cease to grow at 2500 kPa penetration resistance (Kees, 2005; Raper et al., 2005). Bengough et al. (2011) indicated that penetrometer resistance of 2000 kPa occurs even in many relatively moist soils at a matric potential of -100 kPa to -200 kPa, which is enough to inhibit root growth leading to poor plant growth and yields.

Knowledge of the spatial distribution of compacted layer in the field is useful in soil tillage management such as site-specific tillage. Site-specific tillage is geared towards achieving the goals of sustainable agriculture by identifying soil compaction within the field to provide more accurate records to optimize tillage input within the field where root limiting soil compaction exists (Mzuku et al., 2005). In the 1970' and 1980's several studies were conducted in South Africa on soil compaction and root development (Bennie and Laker, 1975; Botha and Bennie, 1982; Bennie and Krynauw, 1985; Mallet et al., 1985). Although, the findings of these studies showed that soil compaction was a problem for crop production in South Africa, but very little has been done since to assess its extent and impacts particularly, in communal irrigation schemes where resources for deep tillage are scarce. Rambuda irrigation scheme is an old communal irrigation scheme where moldboard and disc ploughs have been continually been used to till the land and furrow plough to make planting ridges. These implements only till 22-25 cm of the topsoil (Kílíç et al., 2005). Soils in this irrigation scheme have not been ripped for several years. There is no information on the occurrence and extent of soil compaction in this irrigation scheme, but farmers reported that soils near the access roads were difficult to plough and that there was variation in crop stand and yield both within the plots and across the irrigation scheme (Nethononda and Odhiambo, 2011).

The objective of the study was to determine the soil penetrability and distribution of compacted layer as affected by long-term shallow ploughing in Rambuda irrigation scheme.

Material and Methods

Site description

Rambuda Irrigation Scheme is situated north of Thohoyandou town, between coordinates 22˚59′30″ S and 30˚25′30″E in the Mutale Local Municipality in Vhembe District of Limpopo Province. The total area of the irrigation scheme is 120 ha, demarcated into 104 terraced plots extending from 635-665 m above sea level. Plot sizes vary from 0.6-1.28 ha. The mean annual rainfall is 956 mm, with most rain falling between November and March. The mean minimum average temperature is 15˚C and the mean daily maximum temperature is 27˚C. The topography of the area can be described as virtually flat with gentle undulating slopes varying from 0.5-2%. In general, the soils can be described as deep and well drained with small portions of moderately drained soils in some places. The soils were classified according to the South African Taxonomic system (Soil Classification Working Group 1991), as belonging to the Oakleaf form (*Neocutanic, chromic, luvic; halpic*) sandy clay luvic B horizon and non-luvic loamy sand B1 horizons and Hutton form (*Rhodic, mesotrophic, luvic, halpic*) sandy clay to clay luvic and loamy sand to sandy clay loam non-luvic B horizons. The clay content ranged from 8-46% for the topsoil and 12-52% for the subsoil with average clay contents of 24% and 31% for the topsoil and subsoil, respectively.

Soil penetrability

Soil penetrability was measured as cone penetrometer resistance (PR) was made using the static Rimik CP40II electronic penetrometer with integrated global positioning system and data logger were made after substantial rains when the soil was at field water capacity. Measurements were made on a 100 x 100 m grid across the irrigation scheme using a digitized map with computer generated grid points three day after substantial rain when the soil was at field moisture capacity (ASAE 1999a &b). The map was pre-installed into the GPS used during field measurements, ensuring that measurement points were located properly within the irrigation scheme. The penetrometer was set at 25 mm intervals to minimize errors caused by jittering of CP40II by small pockets of air, stones, roots etc. and a 130 mm^2 cone was used (Rimik, 2004). The maximum insertion speed was set at a minimum speed of 0.2 m/min and a maximum speed of 2 m/min to a depth of 750 mm where soil conditions allowed. Field measurements were uploaded to a computer using the Rimik CP40II Retrieval 6.0 software (Rimik, 2004) for further analysis.

Statistical and geostatistical analysis

Data were subjected to classical statistical analysis for minimum, maximum, mean, standard deviation, skewness (Shapiro and Wilk 1965) and coefficient of variation for 0-30 cm and 30-60 cm soil depths (Tables 1 and 2), using SAS 9.0 (2010). GS+ 9.0 software was used to analyze the spatial structure of the data and to describe the semivariograms (Trangmar et al., 1985; Cambardella et al., 1994; Robertson, 2008). Data were normally distributed and no transformation was necessary. The semivariogram was calculated by the following equation:

$$\gamma(h)= \frac{1}{2N(h)}\left\{\sum_{i=1}^{N(h)}\left[Z(x_i-h)-Z(x_i)\right]^2\right\}, \qquad (1)$$

where *(h)* is the semivariance for intervals class h, $N(h)$ is the number of pairs separated by lag distance which is a the distance between sampling positions = 100 m, $Z(x_i)$ is the measured variable at spatial location i, $Z(x_i+h)$ is the measured variable at spatial distance location $i+h$. There are three parameters which describe the spatial structure of a semivariogram, namely nugget effect (C_0); the sill (C_0+C) and the range. The semivariogram increases with distance between sampling locations, rising to a more or less constant value called the sill at a given separation distance called the range of spatial dependence (Trangmar et al., 1985). The range is the maximum separation distance beyond which there is no longer spatial dependence between the measured variables.

Semivariogram analysis was conducted using a spherical model and ordinary kriging was performed to interpolate spatial distribution of soil compaction across the irrigation scheme. Spatial dependency of PR was described by expressing nugget semivariance as a percentage of the total semivariance (Cambardella et al., 1994). This ratio was used to define distinct classes of spatial dependence for cone penetrometer resistance using the following ratios: if the ratio ≤25%, the variable were strongly spatially dependent; if the ratio was between 25-75%, the variable was considered moderately spatially dependent; and if the ratio >75%, the variable was considered weakly spatially dependent (Cambardella et al. 1994).

Results and Discussion

Soil penetrability

Soil penetrability, which was measured as cone penetrometer resistance is presented in Table 1. The values of all parameters were higher in the subsoil than in the topsoil. The coefficient of variation for the topsoil (36%) and subsoil (21%) exhibited moderate variation according to the guidelines in Wilding and Drees (1983), and Warrick (1997). In general, soil penetrability increased from the topsoil to the subsoil. Cone penetrometer resistance exhibited an increasing trend as depth increased from the mean value of 570.70 to a maximum of 3163 kPa and then declined as the depth increased (Figure 1). The low mean value of 570.70 kPa cone penetrometer resistance observed in the top 0-50 mm may be attributed to loosening of the soil by continuous hand-hoe tillage during weeding and harvesting of crops such as ground nuts and sweet potatoes.

A 150 mm compacted layer was detected between 250 and 400 mm depths (Figure 1). The mean values of

PR increased from the depth of 250-400 mm by between 2580 and >3060 kPa and then declined to less than 2500 kPa. The results showed that the soils at Rambuda irrigation scheme exhibited high values of cone penetrometer resistance and are classified as being moderately to very heavily compacted (Rooney et al. 2005). Kees (2005), indicated that roots of most plants are impeded at 1500 kPa and cease to grow at cone resistance >2500 kPa. The values of PR of the soils at Rambuda irrigation scheme were high enough to impede root growth, water percolation and nutrients redistribution in the soil matrix across the irrigation scheme and consequently produce poor crop growth and yields. Botha and Bennie (1982) reported up to 30% reduction in yield due to soil compaction in maize. The impact of shallow tillage was evident below the 250 mm depth and is evidenced by higher PR values below 250 mm depth. Moldboard and furrow plough tillage depths range from 220-250 mm. The presence of a compacted layer indicates densification of soil by moldboard and furrow ploughs that are continuously used to till the soil in this irrigation scheme. Kílíç et al. (2005) and Júnior et al. (2006) reported similar findings. This indicates the impact of long-term ploughing at shallow depth which densified the subsoil particles over the years. This is critical for root crops such as sweet potato which is the main crop for Rambuda irrigation scheme and suitability of other new crops that are sensitive to soil compaction. Shallow impenetrable layers at 200-300 mm cause poorly shaped roots with shoulders of the roots exposed above the soil resulting in greening (van der Berg and Laurie, 2004).

Spatial variability soil penetrability and distribution of soil compacted layer

The spherical and exponential models were the best fitting to estimate the semivariances for PR for the topsoil and subsoil, repectively. The semivariograms of PR showed a stong spatial dependence with 5 % nugget and moderate spatial dependence with 50 % nugget for the topsoil and subsoil, respectively. The nugget variance (210000) and the sill (430000) were very high compared to the subsoil values (Table 2). Subsoil values of nugget variance, sill and range were lower compared to the topsoil values indicating lack of structured variance. Moderate spatial structure shows that the variation of subsoil PR may be a result of extrinsic variations caused by tillage practices. The range values were greater than

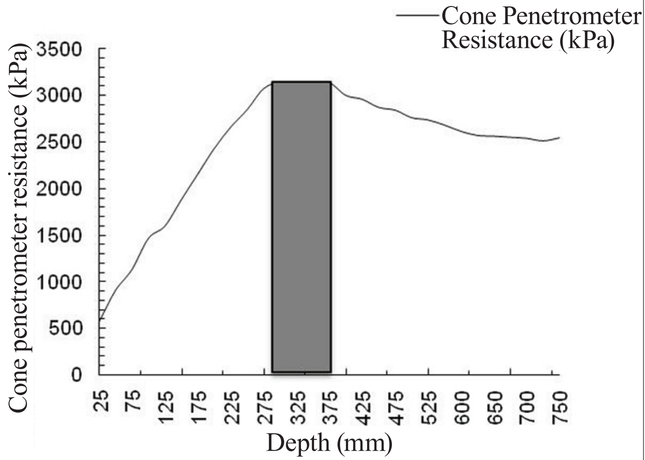

Fig. 1. Mean field measured cone penetrometer resistance (kPa) of the soil across the irrigation scheme

Table 1
Summary statistics of measured soil penetrability

Depth, cm	Cone penetrometer resistance, kPa					CV, %
	Minimum, cm	Maximum, cm	Mean, cm	SD	Skewness	
Topsoil (0-30)	216	3824	1791.68	644.42	0.23	36
Subsoil (30-60)	1775	5215	2975.53	619.40	0.49	21

Table 2
Semivariance analysis of cone resistance

Depth, cm	Cone penetrometer resistance, kPa					
	Model	Nugget	Sill	% Nugget	Spatiality	Range, m
Topsoil (0-30)	Spherical	210000	4300000	5	Strong	169
Subsoil (30-60)	Exponential	18.3	36.07	50	Moderate	368

169 m which is above the sampling distance that was used during the study. This shows the presence of a spatial correlated structure of PR at distance beyond the sample separation distance and, thus the sampling lag distance that was used in this study was sufficient to predict spatial distribution of penetrometer resistance.

Higher spatial variability of compacted layer in the topsoil than in the subsoil may be attributed to continuous shallow tillage, variation in tillage practices such as tractor speed, plough calibrations, state of ploughs and other agronomic practices like application of variable rates and types of organic manure. In general, soil compaction is a serious problem for successful and sustainable crop production at Rambuda irrigation scheme. Rooney et al. (2005) categorized penetrometer resistance into four classes namely, 0-1034 kPa = low, 1034-2038 = medium, 2038-3103 = heavy and >3103 kPa = very heavy. Soils with low (409-1052 kPa) penetrometer resistance for the topsoil were found in theextreme north as well as smaller patches in the east, south east and west. There were small patches of soils with very high PR (>3000) values scattered across the eastern part. This indicates that deterioration of the soil conditions due to soil compaction was not only affecting the subsoil. These figures of high PR are critical for preventing root elongation of important crops such as maize and ground nuts. Bengough et al. (2011) indicated that root elongation of these crops was halved at 2000 kPa.

Subsoil horizons were generally, highly compacted according to categories defined by Rooney et al. (2005). Contour maps showed positional relationship for PR between the topsoil and the subsoil horizons. Consquently, smaller patches of high values of PR in the topsoil were directly underlain by large portions of high values in the subsoil (Figure 2). In general, soil penetrability increased with depth and clay content. Soils with high values of PR (2880 to >3103 kPa) were found in the northeastern tip occupied by luvic *Neocutanic, chromic, luvic* soils with 16-52% clay content, extending to the western part occupied by luvic *Rhodric, mesotrophic, halpic soils*. A patch of soil with medium values of PR (2473-2889 kPa) of subsoil PR occupied the far western tip of luvic clay to sandy clay *Rhodic, mesotrophic, luvic*, northern and south parts of the middle portion of the irrigation scheme while low values were found in the far south-eastern part occupied by non-luvic loamy sand to sandy clay loam *Rhodic, mesotrophic, halpic* soils with 12-14% subsoil clay content. In general, soils with high subsoil clay content exhibited higher PR values than soils with low clay content. The minimum recorded value for subsoil PR was greater than the 2028 kPa minimum level for heavy compaction (Rooney et al., 2005), implying that the subsoil horizons at Rambuda irrigation scheme were heavily compacted. The results showed that the PR of the subsoil was higher than the threshold of 2500 kPa above which roots of most plants cease to grow (Kees 2005). The implications are that plant roots and water are restricted to the top 250 mm of the profile thus reducing the water holding capacity of the soil and consequently leading to poor plant growth and uneven crop stands and low yields (Bennie and Laker, 1975; Bengough et al., 2011).

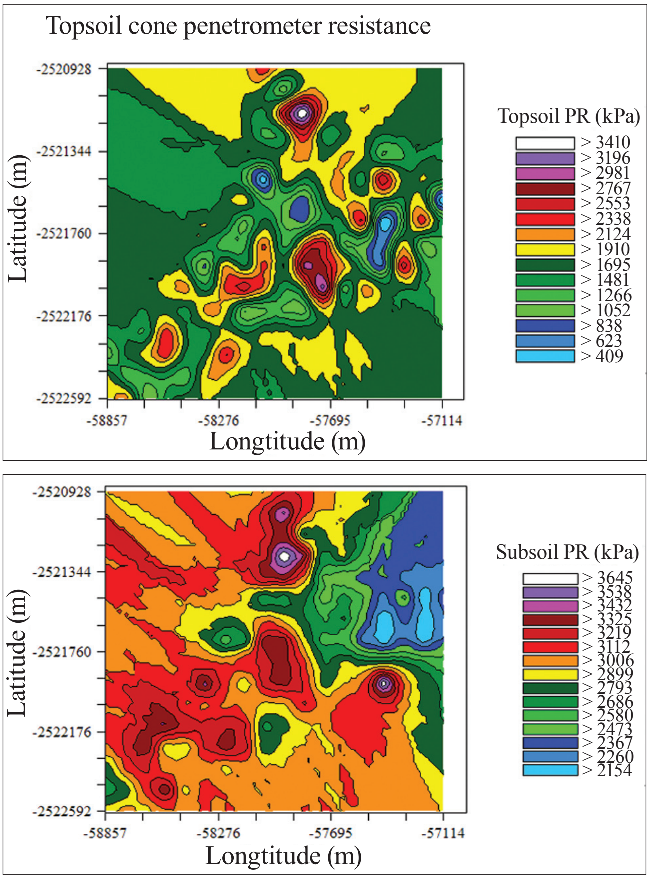

Fig. 2. Semivariograms and kridging maps of cone penetrometer resistance for the topsoil and subsoil horizons

Duirng field measurements of soil penetrability, farmers indicated that the soil had not been ripped for over a ten (10) years. Farmers further complained that yields have been decreasing over the years and there is uneven crop stand within a single plot and across the irrigation scheme. Soil compaction may thus be another cause of spatial variation in crop stands and yield within the plots and across the scheme beside other management practices as reported by the farmers (Nethononda and Odhiambo, 2011).

Conclusions

Long-term shallow ploughing seriously reduced soil penetrability by densifying subsoil layers of the soil. The results showed that soil compaction is indeed a serious problem at Rambuda irrigation scheme caused by continuous shallow tillage of the soil. This is worsened by the lack of deep tillage implements and financial resources to purchase or to hire big contractors. It was also evident that there was a high spatial variability of soil compaction across the irrigation scheme, necessitating the implementation of a variable rate of input management. There is an urgent need for deep tillage of soil at Rambuda irrigation scheme. There is a need for further studies on soil compaction in relation to other soil properties and management practices to design appropriate mitigation strategies under resource-poor communal irrigation schemes in less developed areas. To this end geostatics can be used to present spatial distribution of soil compaction in the form of maps for resource-poor farmer.

Acknowledgements

Authors would like to thank the Khosi Vho-Rambuda, Rambuda Irrigation Scheme Steering Committee, Mr Mukhanu, the Extension Officer for logistics and farmers of Rambuda irrigation scheme for allowing this study to be conducted in their plots and everyone who assisted us in one way or another during this study.

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Received September, 2, 2012; accepted for printing March, 2, 2013.