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Spatial variability in penetration resistance of a hardsetting tropical Alfisol

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Abstract

Geostatistical techniques were used to analyse the spatial variation of penetration resistance on an experimental plot intended for root studies. Penetration resistance was measured at two soil water conditions. Penetration resistance exhibited spatial structure but the models describing the semivariograms were different for the two soil water conditions. An isotropic linear model provided the best fit for penetration resistance in the dry soil while an isotropic spherical model was used for penetration in the wet soil. A complementary study of the spatial structure of water content also showed a similar trend. Cross-semivariograms were constructed to determine the spatial relationship between penetration resistance and water content. Penetration resistance in the dry soil was negatively correlated with water content. The nugget variances as the percentage of the sill in the wet soil data set suggest that the topsoil was slightly more variable than the subsoil. The spatial scale of variation in penetration resistance of the wet soil was 33 m at 7.5 cm depth and 20–27 m at 15–30 cm depth. Punctual kriging was used to estimate the penetration resistance and water content values. The estimated values are presented as contour maps. The pattern of variation and the underlying possible processes for the variation are discussed. The results suggest that the likely influence of spatial variation of soil properties on crop growth may have to be considered in modelling in order to simulate the real field situation.

Introduction

Hardsetting behaviour is suspected to be one of the major soil processes contributing to low productivity of Alfisols in the semiarid tropics. The high soil strength observed in hardsetting soils restricts the timing of land preparation and planting (Ley, 1988) and may restrict root growth when the water content is far from limiting for plant growth (Willcocks, 1981; Mullins et al., 1992a; Ley et al., 1994). A matric potential of -100 kPa appears to be the critical value beyond which further drying of hardsetting soils is likely to reduce root growth by significant proportions (Mullins et al., 1992a). Penetrometer resistance has successfully been used to study the increase in strength as hardsetting soils dry (Young et al., 1991; Mullins et al., 1992a; Ley et al.,

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1994). However, when similar studies were initiated on a hardsetting Alfisol at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) Center in India, considerable variation in penetration resistance was observed within short distances. We were concerned that this large variability will make it difficult to accurately predict or model the effect of soil strength on root growth and subsequently on crop growth on a plot intended for such studies. In previous years the uneven crop growth on this particular plot suggested that spatial variability of soil properties was an important variable to consider before planning a soil management experiment. In this paper we examine the variability in penetration resistance of a hardsetting Alfisol using geostatistical techniques. The theory and use of geostatistics for examining the spatial variation and structure of soil properties have been reviewed in some detail by various authors (Burgess and Webster, 1980a,b; Yost et al., 1982a,b; Greminger et al., 1985; Oliver, 1987; Miyamoto and Cruz, 1987; Trangmar et al., 1987; Lehrsch et al., 1988; Miller et al., 1988; Moolman and Van Huyssteen, 1989). The general concepts can be found in Journel and Huijbregts (1978) and, unless they illustrate a point, they will not be reported in this paper.

Materials and methods

The study was conducted on a 0.2 ha field during the early part of the post-rainy season of 1991/1992 on an Alfisol at ICRISAT, located at Patancheru, India. The soil belongs to the Lingampalli series and is classified as fine mixed Hyperthermic Lithic Rhodustalf. The topography of the site is characterized by a gentle slope of about 0.5% in the east–west direction and of about 1.8% in the north–south direction. Details of some of the physical and chemical properties of the soil are given in El-Swaify et al. (1985).

Prior to making the measurements, the plot was disc harrowed twice to a depth of 12–14 cm and was smoothed using a land planer. The aim of these tillage operations was to establish a uniform soil condition by eliminating any variation caused by previous soil management. These are standard procedures for land preparation at ICRISAT.

Penetration resistance was measured in the field with a hand-held cone penetrometer (Leonard Farnell) developed by the British Army. The penetrometer was fitted with a 30° cone which had a cross-sectional area of 129 mm^2. Measurements were made on two occasions: on a relatively dry soil, and after the soil had been irrigated to saturation and left to drain for 2 days. The penetration resistance measurement scheme consisted of three transects for the first and six transects for the second set of measurements in the north–south direction (along the slope). The transects were 15 m and 6 m apart for the first and second measurements, respectively. Along each transect, 30 penetration resistance measurements were taken at 7.5 cm intervals to 60 cm depth.

Within the transects individual penetration measurements were located 2 m apart. Soil water content was determined gravimetrically at 15 cm intervals to 60 cm depth at the same time as the penetration resistance was measured. Soil samples for water content determination were collected at 4 m intervals along similar transects as for the first set of penetration resistance measurements.

Statistical and geostatistical analyses were performed using GEOPACK software (provided by Dr. S.A. Yates, USDA-ARS). The penetration resistance and water content data were analysed for the mean, standard deviation, variance, skewness, kurtosis and extremes. Subsequently the results were analysed for their spatial dependence using the semivariogram calculated by the relationship (Nielsen et al., 1973)

$$\gamma(h) = (1/2n)\ [z_1(x) - z_1(x+h)]^2 \tag{1}$$

where γ is the semivariance, $\gamma(h)$ is the semivariogram, $z_1(x)$ and $z_1(x+h)$ are the values of the penetration resistance or water content at location x and $(x+h)$ respectively, separated by a distance h. There were n pairs of measurement locations which were distance h apart. To study the spatial correlation between penetration resistance (z_2) and water content (z_1) a cross-semivariogram was estimated by

$$\gamma_{12}(h) = (1/2n)[z_1(x) - z_1(x+h)]\ [z_2(x) - z_2(x+h)] \tag{2}$$

where γ_{12} is the cross-semivariogram, n is the number of pairs of values $\{[z_1(x), z_1(x+h)], [z_2(x), z_2(x+h)]\}$ separated by distance h. Various theoretical models (Gaussian, linear, exponential, spherical and power) were then fitted to the computed semivariograms or cross-semivariograms. The efficiencies of the selected semivariogram models were assessed by a cross-validation procedure. This was achieved by kriging all data points and comparing the kriged values with observed values. The values at unsampled locations were estimated by ordinary kriging using the structural information contained in the semivariogram.

Results and discussion

Variability

Summary statistics for penetration resistance and water content are shown in Tables 2–4. Although penetration resistance measurements were made to a depth of 60 cm, the values below 37.5 cm depth will not be considered in this paper because they contained many off-scale readings, particularly in the dry soil (Table 1). Off-scale readings of penetration resistance are represented by a value of 5 MPa, the upper measurement limit for the penetrometer.

The differences in penetration resistance between the two sets of measure-

Table 1
Percentage of penetration resistance off-scale readings at different depths for the two sampling dates

Depth (cm)	Sampling date	
	29 October 1991	4 November 1991
7.5	17	0
15.0	29	0
22.5	30	5
30.0	30	13
37.5	41	24
45.0	53	39
52.5	62	55
60.0	71	69

Table 2
Summary statistics of penetration resistance (MPa) in the soil

	Depth (cm)				
	7.5	15	22.5	30	37.5
(a) Measured on 29 October 1991					
Number of data values	90	90	90	90	90
Mean	2.38	3.46	3.1	3.26	3.53
Median	1.72	3.28	2.54	2.8	3.1
Standard deviation	1.66	1.16	1.36	1.28	1.33
CV	70	34	44	39	38
Variance	2.729	1.333	1.817	1.631	1.755
Skewness	0.52	0.16	0.47	0.28	−0.06
Kurtosis	1.74	1.57	1.55	1.64	1.50
Minimum	0.17	1.55	1.21	0.77	0.60
Maximum	5.00	5.00	5.00	5.00	5.00
(b) Measured on 4 November 1991					
Number of data values	180	180	180	180	180
Mean	0.30	1.54	1.68	2.20	2.80
Median	0.17	1.38	1.38	1.72	2.24
Standard deviation	0.29	0.72	0.95	1.19	1.36
CV	97	47	57	54	49
Variance	0.084	0.523	0.900	1.420	1.840
Skewness	2.24	1.72	2.28	1.56	0.76
Kurtosis	7.94	7.78	8.20	4.10	2.00
Minimum	0.09	0.35	0.52	0.69	0.52
Maximum	1.72	5.00	5.00	5.00	5.00

CV, Coefficient of variation (%).

ments demonstrate the important influence of water content on the strength of these soils. Doubling the water content reduced the penetration resistance by 56–87% in the topsoil (0–15 cm depth) while an approximately 10% in-

Table 3
Summary statistics of the logarithm of penetration resistance, log(PR+1), in the soil (measured on 4 November 1991)

	Depth (cm)				
	7.5	15	22.5	30	37.5
Number of data values	180	180	180	180	180
Mean	0.24	0.09	0.94	1.11	1.23
Median	0.16	0.87	0.87	1.00	1.18
Standard deviation	0.19	0.26	0.29	0.31	0.34
CV	79	29	30	28	27
Variance	0.035	0.065	0.081	0.098	0.114
Skewness	1.82	0.60	1.39	1.13	0.42
Kurtosis	5.61	3.96	5.05	3.41	2.08
Minimum	0.08	0.30	0.42	0.53	0.42
Maximum	1.00	1.79	1.79	1.79	1.79

CV, Coefficient of variation (%).

Table 4
Summary statistics of water content ($g\,g^{-1}$) in the soil

	Depth (cm)			
	0–15	15–30	30–45	45–60
(a) Measured on 29 October 1991				
Number of data values	48	48	48	48
Mean	0.08	0.15	0.15	0.13
Median	0.09	0.15	0.16	0.13
Standard deviation	0.017	0.028	0.026	0.026
CV	21	19	17	20
Variance	0.000	0.001	0.001	0.001
Skewness	−0.123	−0.862	−0.924	−0.470
Kurtosis	2.80	3.27	3.17	2.79
Minimum	0.04	0.06	0.07	0.07
Maximum	0.12	0.19	0.19	0.18
(b) Measured on 4 November 1991				
Number of data values	48	48	48	48
Mean	0.17	0.16	0.17	0.15
Median	0.18	0.16	0.18	0.15
Standard deviation	0.021	0.025	0.027	0.034
CV	12	16	16	23
Variance	0.0004	0.0006	0.0069	0.0011
Skewness	−0.076	−0.276	−1.161	−0.743
Kurtosis	2.44	2.53	3.78	4.07
Minimum	0.13	0.09	0.10	0.04
Maximum	0.22	0.20	0.21	0.23

CV, Coefficient of variation (%).

crease in water content in the subsoil reduced penetration resistance by about 21–46%. Under dry soil conditions (the first set of measurements), spatial differences in penetration resistance were significantly and negatively related to spatial differences in water content in the topsoil, although the coefficient of correlation was rather low ($r=0.43$, $P=0.01$). This dependence of penetration resistance on water content was not observed in the subsoil as these two properties varied with depth and it appears that the spatial variation in penetration resistance in the subsoil is more severely affected by other soil properties. Clay and gravel contents increase with depth in this soil (El-Swaifv et al., 1985) and the latter may be responsible for the large number of off-scale readings in the subsoil. In this study the mean bulk density (uncorrected for gravel content) measured after disc harrowing and one irrigation increased from 1.68 Mg m^{-3} at 7.5 cm depth to 1.73 Mg m^{-3} at 15 cm depth and then decreased (to about 1.55 Mg m^{-3}) with depth to 37.5 cm. The mean bulk density below 37.5 cm was about 1.80 Mg m^{-3}.

As shown by the coefficient of variation (CV), the variability of penetration resistance was greater at 7.5 cm depth than at 15–37.5 cm depth in both sets of measurements but was greater for the wet soil than for the dry soil (Table 2). Conversely, the variability in water content was generally greater for the dry soil than for wet soil (Table 4). While variability in water content was roughly the same at all depths in the dry soil, it increased with depth in the wet soil and this may reflect differences in water movement in the subsoil as a result of variation in hydraulic properties of the soil.

The deviations of penetration resistance and water content from a normal distribution were evaluated by the coefficient of skewness (Tables 2–4), frequency histograms and the Kolomogorov–Smirnov test (not shown). The coefficient of skewness and the frequency histograms showed that the distribution of penetration resistance was positively skewed and appeared to be more skewed in the wet soil than in the dry soil (Table 2). In contrast, the distribution of water content was skewed towards lower values and did not indicate any clear difference between a dry soil and a wet soil (Table 4). However, for each set of measurements of water content, the coefficient of skewness was smallest at 0–15 cm and greatest at 30–45 cm depths. The opposite signs in the skewness of penetration resistance and of water content suggest a negative relationship between these two soil properties.

Tests for normality using the Kolomogorov–Smirnov test showed that penetration resistance for both soil conditions did not follow the normal distribution pattern, even when the data were log-transformed. Nevertheless, the coefficients of skewness (Table 2) and the frequency histograms (not shown) show that the penetration resistance in the dry soil could be approximated by a normal distribution. In contrast, the penetration resistance observations in wet soil approximately followed a log-normal distribution and the data were log-transformed, $\log(PR+1)$ for subsequent geostatistical analyses (Table 3).

A value of 1 was added to make the transformed data positive. The log-transformed data had smaller CVs than the original data (Table 3).

Based on the three normality tests, the water content observations were approximated by a normal distribution at depths of 0–15 and 45–60 cm in the dry soil and at depths < 30 cm in the wet soil. The remaining water content observations were approximately assumed to be log-normally distributed.

Spatial structure analysis

Semivariograms were used to study the spatial dependence of penetration resistance and water content. Examples of the experimental semivariograms of the data sets calculated using Eq. (1) are given in Figs. 1 and 2. These show that the two soil properties were spatially dependent at the scale used. However, no directional dependency (anisotropy) was observed. While the semivariances appeared to be unbounded for the dry soil, they increased with distance (h) for the wet soil until they stabilized around a limiting value (the sill). To describe the semivariograms and to provide the information for kriging, each of the experimental semivariograms was fitted to a theoretical semivariogram of positive definite type. Using the least-squares approximation

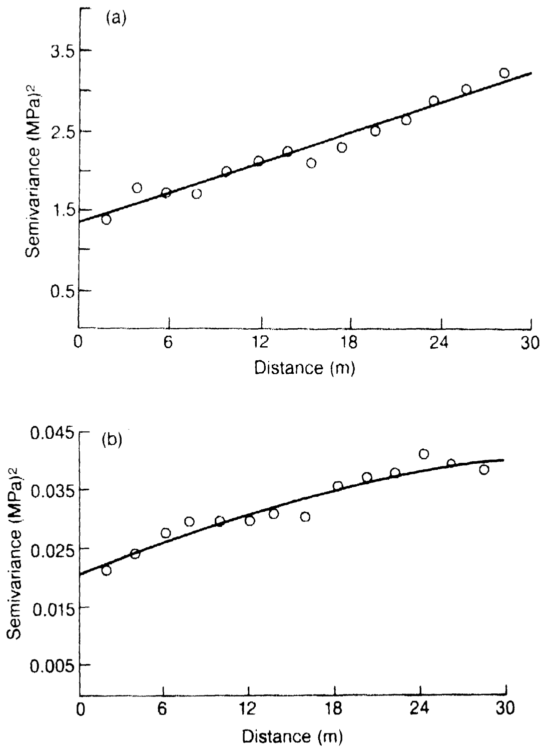

Fig. 1. Experimental (symbols) and theoretical (solid lines) semivariograms of penetration resistance (PR) at 7.5 cm depth measured on (a) 29 October 1991 and (b) 4 November 1991. Semivariances for (b) were of log(PR + 1).

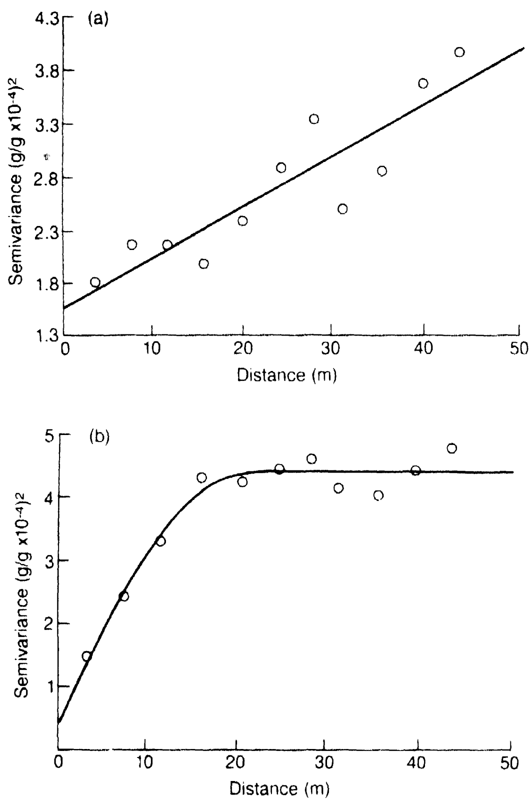

Fig. 2. Experimental (symbols) and theoretical (solid lines) semivariograms of water content at 0–15 cm depth measured on (a) 29 October 1991 and (b) 4 November 1991.

(McBratney and Webster, 1986), a linear model, Eq. (3), was fitted to the experimental semivariogram of dry soil penetration resistance and water content (Table 5 and Figs. 1(a) and 2(a)):

$$\gamma(h) = C_o + bh \tag{3}$$

where C_o is the nugget variance, h is the distance and b is the slope. A spherical model, Eqs. (4) and (5), was used for wet soil properties (Table 5 and Figs. 1(b) and 2(b)):

$$\gamma(h) = C_o + c\{(3/2)(h/a) - (1/2)(h/a)^3\} \quad \text{for } h \leq a \tag{4}$$

$$\gamma(h) = C_o + c \quad \text{for } h > a \tag{5}$$

where c is the a priori variance of the autocorrelated structure, a is the range of the structure, and other parameters are as for Eq. (3). For both models, the γ-intercept is the nugget variance which provides an indication of short distance variation. The range or zone of influence of the semivariogram with a spherical model is the distance (h) at which γ attains the maximum value (sill). Often the sill is approximately equal to the sample variance (Journel and Huijbregts, 1978). Measured properties closer than the range are spa-

Table 5
Summary of semivariogram models

Variable	Depth (cm)	Model	Nugget[1]	Sill[1]	Range (m)
(a) Measured on 29 October 1991					
PR	7.5	Linear	1.30	–	–
	15.0	Linear	0.71	–	–
	22.5	Linear	0.77	–	–
	30.0	Linear	0.79	–	–
WC	0–15	Linear	0.0001	–	–
	15–30	#	#	–	–
(b) Measured on 4 November 1991					
PR[2]	7.5	Spherical	0.020	0.040	33
	15.0	Spherical	0.048	0.065	20
	22.5	Spherical	0.060	0.089	26
	30.0	Spherical	0.079	0.111	27
WC	0–15	Spherical	0.0003	0 0044	20
	15–30	Spherical	0.0033	0.0066	20

[1]Units for PR are $(MPa)^2$ and WC are $(g\ g^{-1})^2$.
[2]Data log-transformed: log(PR + 1).
PR, Penetration resistance; WC, water content; #, no pattern.

tially dependent or more alike whereas those further apart are independent (Burgess and Webster, 1980a). The semivariogram with a linear model has no sill or range.

The results of the cross-validation showed that the selected semivariograms adequately described the spatial behaviour of penetration resistance but not water content. The poor fit for water content was attributed to the small data set available for the semivariogram calculation. The major difference between the semivariograms at the two water contents is their spatial scale. The variation of the two soil properties occurred on a much larger scale for dry soil than for wet soil. The semivariances of the penetration resistance for the topsoil were greater than for the subsoil. This is consistent with the calculated CVs. The nugget variance contributed about 58 and 73–81% of the total variability of wet soil penetration resistance in the topsoil and subsoil, respectively. The spatial scales of variation (zone of influence) in penetration resistance for wet soil were smaller at 15–30 cm depth than at 7.5 cm depth. This reflects the lesser influence of soil management on the subsoil than on the surface soil. The spatial scales of variation in water content were similar at the two depths with 6.8% and 50% of total variation in the nugget effects for topsoil and subsoil, respectively.

Cross-semivariograms were calculated using Eq. (2) to investigate the spatial correlation between penetration resistance and water content. A representative experimental cross-semivariogram is shown in Fig. 3. A linear model with a nugget effect was fitted to the experimental cross-semivariogram and

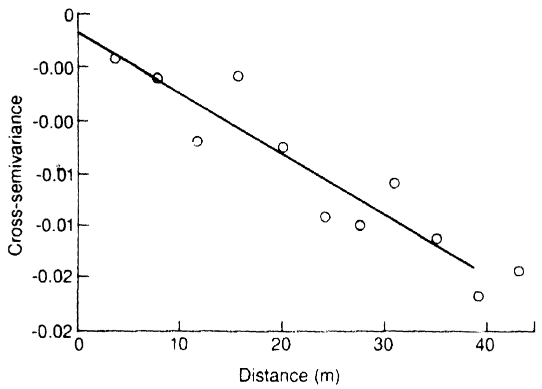

Fig. 3. Experimental (symbols) and theoretical (solid lines) cross-semivariogram between penetration resistance and water content at 0–15 cm depth on 29 October 1991.

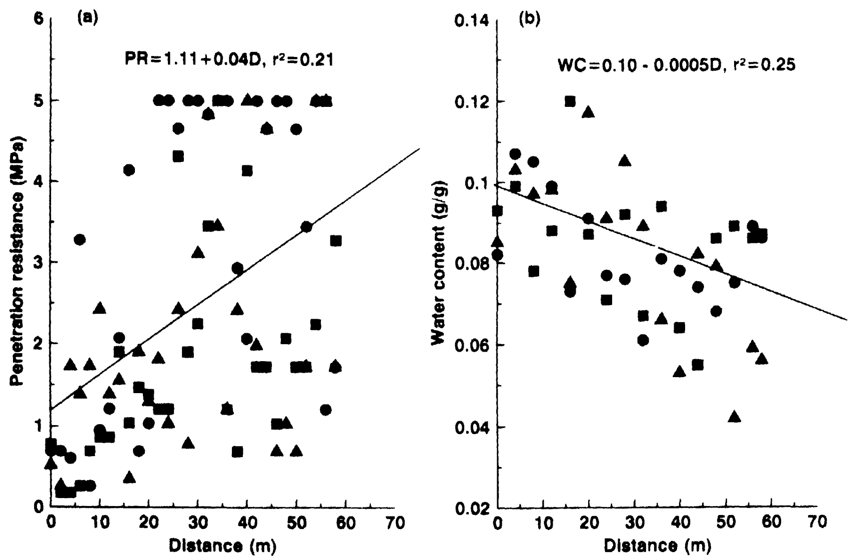

Fig. 4. Variation of (a) penetration resistance and (b) water content along the three transects on 29 October 1991. The symbols (●), (■) and (▲) represent the first, second and third transects, respectively. The solid lines are fitted regressions of pooled data, $P < 0.001$.

is also shown in Fig. 3. It shows that the penetration resistance of the dry topsoil was negatively correlated with water content, as suggested earlier.

We observed a small but significant ($P = 0.001$) linear trend of penetration resistance with distance in the dry soil and water content with distance for both dry and wet soils when a regression analysis (e.g. Fig. 4) was done. This shows lack of strict stationarity in sample properties. Stationarity in the data set is one of the key assumptions in geostatistics (Journel and Huijbregts, 1978). Semivariograms and kriging techniques sometimes give erroneous and biased results if a significant trend is ignored (Hamlett et al., 1986). Other workers found semivariograms to be robust enough to accommodate deviations from strict stationarity (Webster and Burgess, 1980; Yost et al., 1982b). Although there are several options for dealing with trend in semivariogram analysis (David, 1977; Webster and Burgess, 1980; Davidoff et al., 1986; Hamlett et al., 1986), none was included in our study and this may form a limitation to inferences made on the dry soil data set. However, no trend was observed in the penetration resistance of wet soil and the sill values of the estimated semivariograms were generally similar to the sample variance, which supports the general observation of no trends across the experimental plot.

Estimation of the soil properties

Using the information contained in the semivariogram models (Table 5) and the sample data, the values of penetration resistance and water content were estimated over the experimental plot by punctual kriging (Burgess and

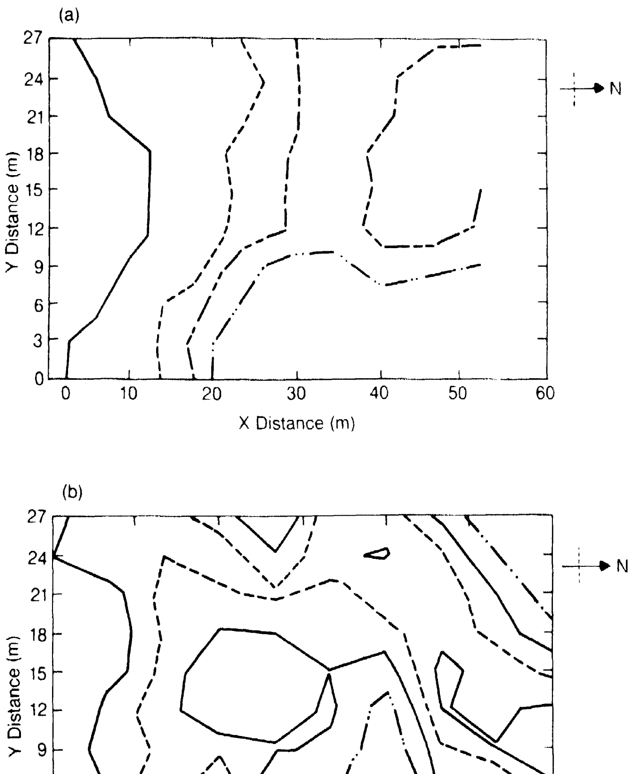

Fig. 5. Contour maps of kriging estimates of penetration resistance at 7.5 cm depth on (a) 29 October 1991 and (b) 4 November 1991. The symbols (——), (– – –), (···) and (–··–··–) represent values of penetration resistance for (a) of 1.0, 1.81, 2.42 and 3.07 MPa, respectively, and for (b) of 0.16, 0.19, 0.21 and 0.26 [log(MPa+1)], respectively.

Webster, 1980a). Figures 5 and 6 show the contour maps of the estimated values. The maps show that generally the north and the north-west part of the plot had a greater penetration resistance and lower water content than the southern part. This pattern is more evident in the dry soil than in the wet soil. The pattern also confirms the relationship between the two soil properties.

The main factors contributing to the distribution of the soil properties is probably soil erosion and runoff loss. These soils readily form a dense crust with low hydraulic conductivity under raindrop impact. Despite the small slope, significant runoff was observed during irrigation and it is possible that low lying areas retained water for longer periods than the upper part of the plot. Some soil erosion was also observed during irrigation and its cumulative effects from previous rainfall events was inferred from the depth to the undecomposed horizon (murrum layer). The minimum depth to the murrum layer was approximately 40 cm at the north end of the plot and it increased

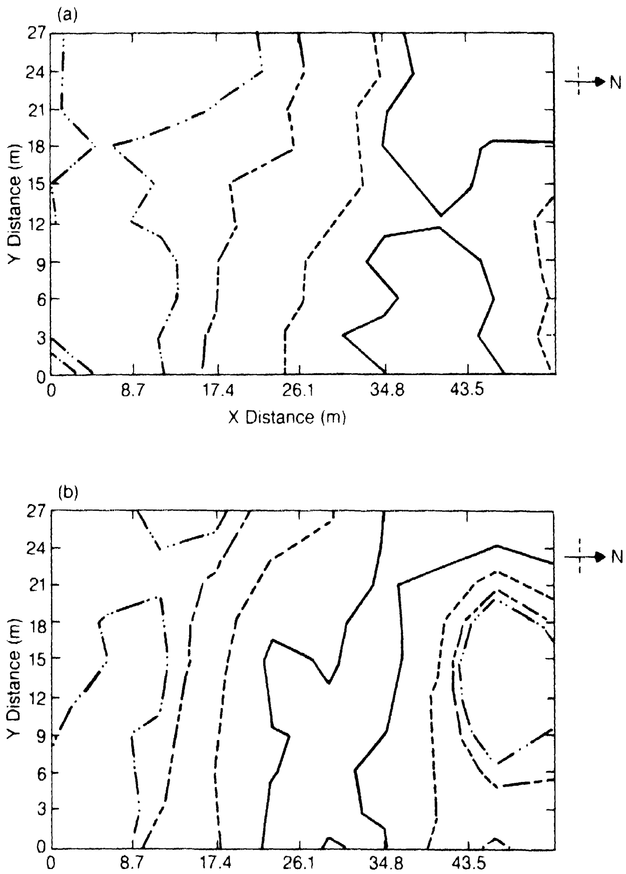

Fig. 6. Contour maps of kriging estimates of water content at 0–15 cm depth on (a) 29 October 1991 and (b) 4 November 1991. The symbols (——), (---), -------) and (-··-··-) represent water contents for (a) of 0.075, 0.080, 0.089 and 0.093 g g^{-1}, respectively, and for (b) of 0.162, 0.174, 0.183 and 0.187 g g^{-1}, respectively.

progressively to 60 cm at the south end of the plot. This was likely to influence clay content distribution, and hence the distribution of water content and penetration resistance distribution. However, clay content determined at 10 m intervals along the slope in the middle transect and random hand-texturing did not reveal significant trends (not shown). A weed control experiment was conducted for three seasons prior to our measurements and the differences in weed infestation and alleys separating the experimental plots are also likely to have influenced the distribution of penetration resistance and water content.

This study also provided some information on the profile-hardening character of the soil. The soil was too hard to disc harrow until it was wetted by 18 mm of rainfall on 22 October 1991. Although the plot was disc harrowed twice before the measurements on 29 October 1991, the penetration resistance values were in excess of 2 MPa throughout the profile (Table 2). Irrigation substantially reduced the penetration resistance (Table 2). Therefore one of the strategies to manage this soil that exhibits hardsetting behaviour is to adopt management practices that minimize runoff and conserve water (Smith et al., 1992) so as to maintain soil strength below critical levels for root growth. The mulch-based systems have been shown to create such properties (Smith et al., 1992).

Conclusions

This study examined the spatial structure of penetration resistance at two soil water conditions. The data sets produced different shapes of semivariograms. Penetration resistance in the dry soil varied isotropically with a linear model while a spherical model described the semivariograms of the soil when wet. These results suggest, as in many other studies, that penetration resistance should be measured under conditions of similar water content when comparing data sets from soil management treatments.

The spatial structure showed that the topsoil was more variable than the subsoil. This was attributed to soil management, which we assume was the main source of variation, having a greater influence in the topsoil than in the subsoil. The data set of the wet soil showed extremely high nugget variances suggesting large-scale local variation in penetration resistance. Factors contributing to the large variances include measurement and random errors, and variation at scales smaller than the sampling scale.

These results have important implications for crop growth modelling. The spatial pattern of roots in the soil is likely to be influenced by penetration resistance and water content, thus limiting the applicability of many crop growth models which assume uniform distribution of roots at each soil depth. The likely influence of spatial variation of soil properties on crop growth may have to be considered in modelling in order to simulate the real field situation.

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