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Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard

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Abstract

Frequent machinery traffic on sloping vineyard influences spatial distribution of soil physical properties. Our objective was to assess the effects of crawler tractor traffic across the slope (20%) on spatial distribution of soil strength and water content of silt loam soil under controlled grass cover and conventionally cultivated vineyard. The experiment was situated on hillside vineyard (NW, Italy) arranged with rows crosswise the slope. The grass covered treatment included periodical mowing and chopping of herbs and the cultivated treatment—autumn ploughing (18 cm) and spring and summer rotary-hoeing in the vineyard inter-rows (2.7 m). A crawler tractor (2.82 Mg) was used at the same locations across the slope for all tillage and chemical operations. The measurements of soil bulk density, penetration resistance and volumetric water content were done in autumn (after vintage) within the sloping inter-row. The results were analyzed using classic statistics and geostatistics with and without trend. The highest variability was obtained for penetration resistance (CV 56.6%) and the lowest for bulk density (9.6%). In most cases, the semivariograms of the soil parameters were well described by spherical models. The semivariance parameters of all properties measured were influenced by trend. Three-dimensional (3D) maps well identified areas with the highest soil strength in lower crawler ruts being positioned in the upper side of vine row and successively lower strength in upper ruts situated on other side of the same row and inter-rut area. Higher strength in lower than upper ruts was induced by tractor's tilt and resulting higher ground contact pressure. Soil water content in both treatments was the lowest below the upper rut and increased in inter-rut and lower rut areas. The differences in the soil properties between the places within the inter-row were more pronounced in grass covered than in cultivated soil.

Keywords: Penetration resistance; Bulk density; Water content; Sloping vineyard; Management; Spatial effects

1. Introduction

Alterations in soil structure due to topsoil and subsoil compaction by vehicular traffic influence many soil properties which control crop production and quality of

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the environment (Soane and Ouwerkerk, 1995). Negative effects of subsoil compaction are persistent and possibilities of loosening are disappointing (Håkansson and Reeder, 1994; Horn et al., 2000; Van den Akker et al., 2003). Therefore, better knowledge of the effects is needed to identify prevention strategies.

Soil in vineyards is subject to frequent tractor traffic associated with soil tillage, the application of chemicals and grape harvesting. In highly mechanized viticulture, the number of tractor passes per year can be up to 22 in traditionally cultivated and 20% less in grass covered vineyards (Lisa et al., 1995). In addition controlled grass cover management has been suggested to prevent soil structural degradation and erosion and to improve soil trafficability and workability (Lisa et al., 1991; Bazzoffi and Chisci, 1999). In dry years, the controlled grass cover management reduced plant vigor and grape production, though of better quality (Lisa et al., 1991). Usually ruts produced by wheeled or crawler tractors in vineyards have permanent locations within the inter-row distance varying usually from 2.0 to 2.7 m (Lisa et al., 1993; Van Dijck and van Asch, 2002). The pressure exerted on the contact surface of the track varies in function of the tractor size and of the slope. The mass of commonly used tractors ranges from 2.6 to 3.7 Mg and the width from 1.15 to 1.40 m, and therefore, the ruts are situated near the vine row and thus may affect soil conditions within the root zone.

Very little research has been done to investigate soil compaction effects in vineyards. Few papers showed (Ferrero et al., 2001; Van Dijck and van Asch, 2002) that long-term traffic in vineyards results in topsoil and subsoil compaction below the frequent tillage depth. Van Dijck and van Asch (2002) revealed that subsoil compaction in a vineyard is mostly attributed to wheel load. In sloping vineyards with rows across the slope, this load and associated ground contact pressure can be greater beneath a running gear in the lower than upper portions of the slope owing to tilt of the tractor. Compactive effects of this uneven loading can be enhanced by soil water contents that are usually higher in lower parts of the slope. The extent and depth of the resulting compaction depend on whether soil is under grass or cultivated due to different internal strength and associated susceptibility to compaction. Useful tools in quantifying spatial effects of soil compaction on behavioral soil physical properties are geostatistical techniques. The knowledge of spatial and temporal patterns of soil characteristics at field scale is a useful tool in ‘precision agriculture’ (Perez-Quezada et al., 2003).

The aim of this study was to determine the effects of tractor traffic across the slope on spatial distribution of soil bulk density, penetration resistance and water content under grass cover and conventional cultivation in the inter-rows of hill sloping vineyard.

2. Material and methods

2.1. Soil and treatments

The experiment was carried out at a site representative of Piedmontese hillside viticulture (NW, Italy), at 450 m elevation with an average slope of 20% and south/southwest aspect. Long-term annual rainfall averages 840 mm and cold winter with snow and dry summer with rainstorms characterize the climate. The vineyard, with rows following the contour lines, lies on silt loam soil (USDA, 1962, revised) resting on marls (middle Miocene) and contains on average 33% sand, 58% loam, 9% clay and 3% of organic matter. Water contents at field capacity at 0–10 and 10–20 cm depths were 36.7% and 35.1% by volume, respectively. The soil of the vineyard is Eutrochrepts according to the soil taxonomy (USDA, 1975). In the permanent grass cover treatment (G), a mixture of *Lolium italicum* L. and *Trifolium repens* L. was seeded 10 years before, though at the time of the experiment local flora and broad-leaved plants occurred. The permanent grass cover treatment (G) included three mowing and chopping operations of herbs left on the ground, one chemical weed control under the row, and fertilization by a subsoil distributor to drill the fertilizer to 15–20 cm depth in the middle of the inter-row. Conventional cultivation treatment (C) included autumn ploughing (18 cm) and rotary-hoeing in spring and summer to incorporate the herbs with the soil to 10 cm depth. These treatments were applied in the vineyard for 10 years.

In both treatments, a crawler tractor (Fiat 55 CV) of 2.82 Mg weight and 1.31 m width was used along the inter-rows across the slope at the same locations. On average, 14 and 11 tractor passes were performed in G and C, respectively. The width and length of each track being in contact with the ground were 0.3 and 1.4 m,

Fig. 1. Surface deformation caused by crawler tracks across the vineyard slope. Left side: upper track; right side: lower track.

respectively. Ground contact pressures as calculated from the weight and maximum soil slope using the general equations of moments, were some 27.4 and 38.0 kPa for upper and lower tracks, respectively. This resulted in a greater surface deformation or rut depth under the lower than upper tracks along the slope and to a higher extent in cultivated (Fig. 1) than grass covered soil.

2.2. Measurements of soil physical properties

The study included one plot (30 m long and 2.7 width) in each treatment (Fig. 2). The plots were chosen on two alignments (the same for the two treatments) along the hillslope. The measurements were performed on four transects in each plot (Fig. 2). The measurements of penetration resistance, bulk density and volumetric water content were done in places corresponding to upper rut, inter-rut and lower rut areas. The survey was performed in October 2001 that being most critical period for machinery traffic; annual rainfalls for this year were 507.8 mm (spring 217.2 mm, summer 82.2 mm and autumn 159.6 mm). Soil penetration resistance was measured by means of a recording penetrometer with a cone angle of 30° and 1 cm^2 area (Walczak et al., 1973) to a depth of 25 cm with vertical separation distance of 2.5 cm. The number of measurement for each separation distance was 36 and the total number was 360.

Bulk density of soil was determined in places near measuring points of penetration resistance (Fig. 2) by the core method (Blake and Hartge, 1986) at depths: 2.5–7.5, 10–15 and 17.5–22.5 cm using 100 cm^3 cores. The same cores were used to determine gravimetric soil water content. Volumetric water content was calculated on the basis of gravimetric water content and bulk density. Total number of measurement data for each parameter was 36.

To analyse and visualise the results in 3D maps, GeoEas (Englund and Sparks, 1988) and GS+ (Gamma Design Software, 1998) software were used.

3. Results and discussion

3.1. Summary statistics

Changes in soil structure resulting from compaction by tractor traffic are reflected in changes in bulk

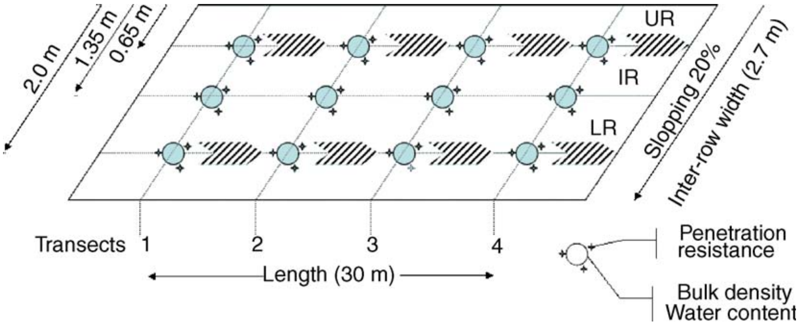

Fig. 2. The study inter-rows and sampling points locations. UR: upper rut; IR: inter-rut; LR: lower rut.

Table 1
Summary basic statistics of soil bulk density, penetration resistance and water content

Statistics	Grass covered			Cultivated		
	Resistance (MPa)	Bulk density (Mg m^{-3})	Water content (m^3 m^{-3})	Resistance (MPa)	Bulk density (Mg m^{-3})	Water content (m^3 m^{-3})
N used	360	36	36	360	36	36
Mean	3.821	1.232	0.190	2.706	1.233	0.204
Variance	3.814	0.014	0.004	2.347	0.005	0.003
Standard deviation	1.953	0.119	0.066	1.532	0.074	0.056
Coefficient variance	51.1	9.6	34.9	56.6	6.0	27.7
Skewness	0.51	−0.71	0.94	0.68	−0.17	1.51
Kurtosis	2.69	2.37	2.95	2.69	1.97	6.14
Minimum	0.5	0.96	0.096	0.5	1.1	0.100
Twenty-fifth percentile	2.3	1.15	0.137	1.5	1.16	0.179
Median	3.5	1.265	0.181	2.4	1.245	0.194
Seventy-fifth percentile	5.2	1.32	0.21	3.7	1.29	0.216
Maximum	9.3	1.41	0.343	7.7	1.36	0.376

density, penetration resistance and water content. Basic statistical characteristics of the measurements are presented in Table 1.

Mean penetration resistance was considerably higher under G than C whereas mean soil bulk density and water content were similar in both treatments. Penetration resistance data varied in a wide range from 0.5 to 9.3 MPa and was highly variable (CV 51.1–56.6%).

The ranges for bulk density and volumetric water content were 0.96–1.41 Mg m^{-3} and 0.096–0.376 m^3 m^{-3}, respectively. Compared with penetration resistance, both characteristics were less variable. Higher variability of penetration resistance than bulk density confirms the results of earlier studies (Warrick and Nielsen, 1980; Utset and Cid, 2001).

In both treatments, the skewness was highest for water content distribution (0.94–1.51) and succes-

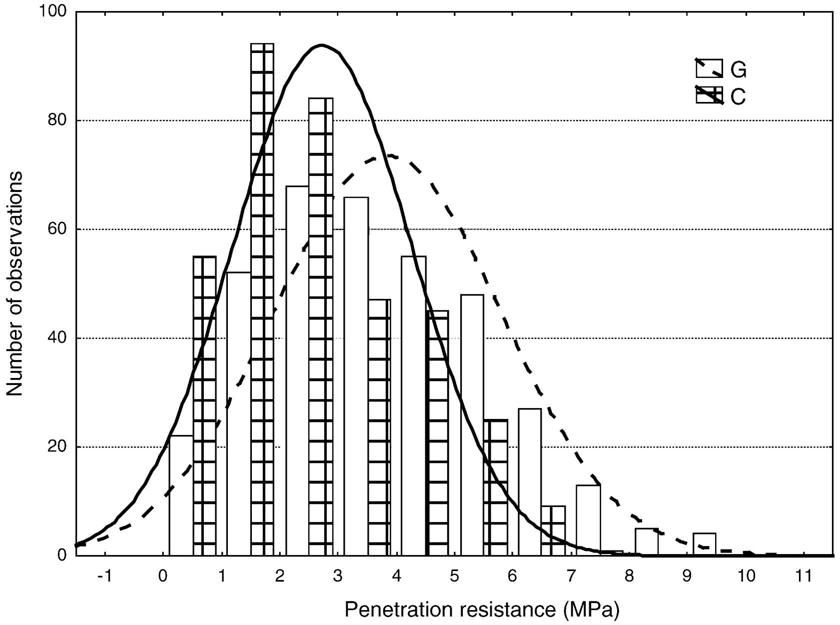

Fig. 3. Histograms of penetration resistance under grassed (G) and cultivated (C) vineyard.

Table 2
Correlation matrix for the analysed variables under grass covered and conventionally cultivated soil

	Grass PR	Cultivated PR	Grass BD	Grass WC	Cultivated BD	Cultivated WC
Grass PR	1.0	**0.718**	**0.581**	−0.059	**0.429**	0.024
Cultivated PR		1.0	**0.530**	−0.148	**0.493**	−0.028
Grass BD			1.0	0.048	**0.576**	**−0.199**
Grass WC				1.0	−0.141	**0.246**
Cultivated BD					1.0	−0.080
Cultivated WC						1.0

PR (MPa): penetration resistance; BD (Mg m^{-3}): bulk density; WC (m^3 m^{-3}): water content. Correlation coefficients presented in bold are statistically significant >95% of probability.

sively decreased for penetration resistance (0.51–0.68) and bulk density (−0.17 to −0.71). The data of bulk density were more skewed under G than C and the inverse was true for the data of water content. The kurtosis values of all the parameters under G were similar (2.37–2.95) indicating near normal data distribution. Much higher kurtosis of water content under C (6.14) indicates that the distribution curve is relatively steep at the centre and has longer tails.

As can be seen from Fig. 3, the frequency distribution of penetration resistance is normal in both G and C. A normal distribution can also be fitted to bulk density and water content variability. Less agreement with normal distribution was obtained after a log-natural transformation of the data.

Table 2 presents the correlation coefficients among the parameters studied. The coefficients confirmed a positive relationship between bulk density and penetration resistance for the upper 25 cm soil layer under both G ($R = 0.58$) and C ($R = 0.49$). However, there was not significant correlation between soil water content and penetration resistance, which can be attributed to relatively low range of water contents of most measurement results.

3.2. Geostatistical analysis

Some anisotropy in penetration resistance was found using surface semivariograms (Fig. 4a). Azimuth angles of the anisotropy in reference to surface of the slope were 27° and 16° for G and C, respectively. This anisotropy could be associated with depth over the distance from upper to lower crawler rut and it was considered while constructing omnidirectional semivariograms. Anisotropy of penetration resistance within the depth (0.03–0.15 m) relative to direction of traffic was reported by Lapen et al. (2001). Anisotropy of water content data was up to 56° under G and 90° under C (Fig. 4c) and was probably associated with the effects of traffic lanes and shadow by vine trees. Much smaller anisotropy (8–9°) in both treatments was observed for bulk density (Fig. 4b). The values of anisotropy could be also influenced by presence of deterministic element (trend) of the data analyzed.

Isotropic semivariograms of penetration resistance, bulk density and water content have been constructed for G and C treatments. In six of seven cases, the best fit from the experimental data was obtained for the spherical model. Examples of the semivariograms for mean penetration resistance in the G and C are shown in Fig. 5a and b. The semivariance of sill being approximately 2.3 MPa^2 under C and 4.1 MPa^2 under G imply greater dispersion of the results under G. In both treatments, the semivariance, as calculated with classic statistics (Table 1), was similar compared to that obtained with geostatistical methods. This similarity implies lack of short and long range trends and justifies the use of geostatistical methods.

The data in Table 3 show that the mean range (the distance over which the semivariance increases) is greater under G (0.755 m) than under C (0.585 m). This implies that sampling interval for representative results should be smaller under G. The semivariance as expressed by the nugget was much greater under C (0.51) than G (0.36). Bulk density and water content data had similar ranges under G (0.76–0.8 m) and under C (0.83–0.95 m).

Values of proportion of spatial structure $C_s/(C_0 + C_s)$ being a measure of the proportion of sample variance ($C_0 + C_s$) that is explained by spatially structured variance (C_s) were greater for penetration

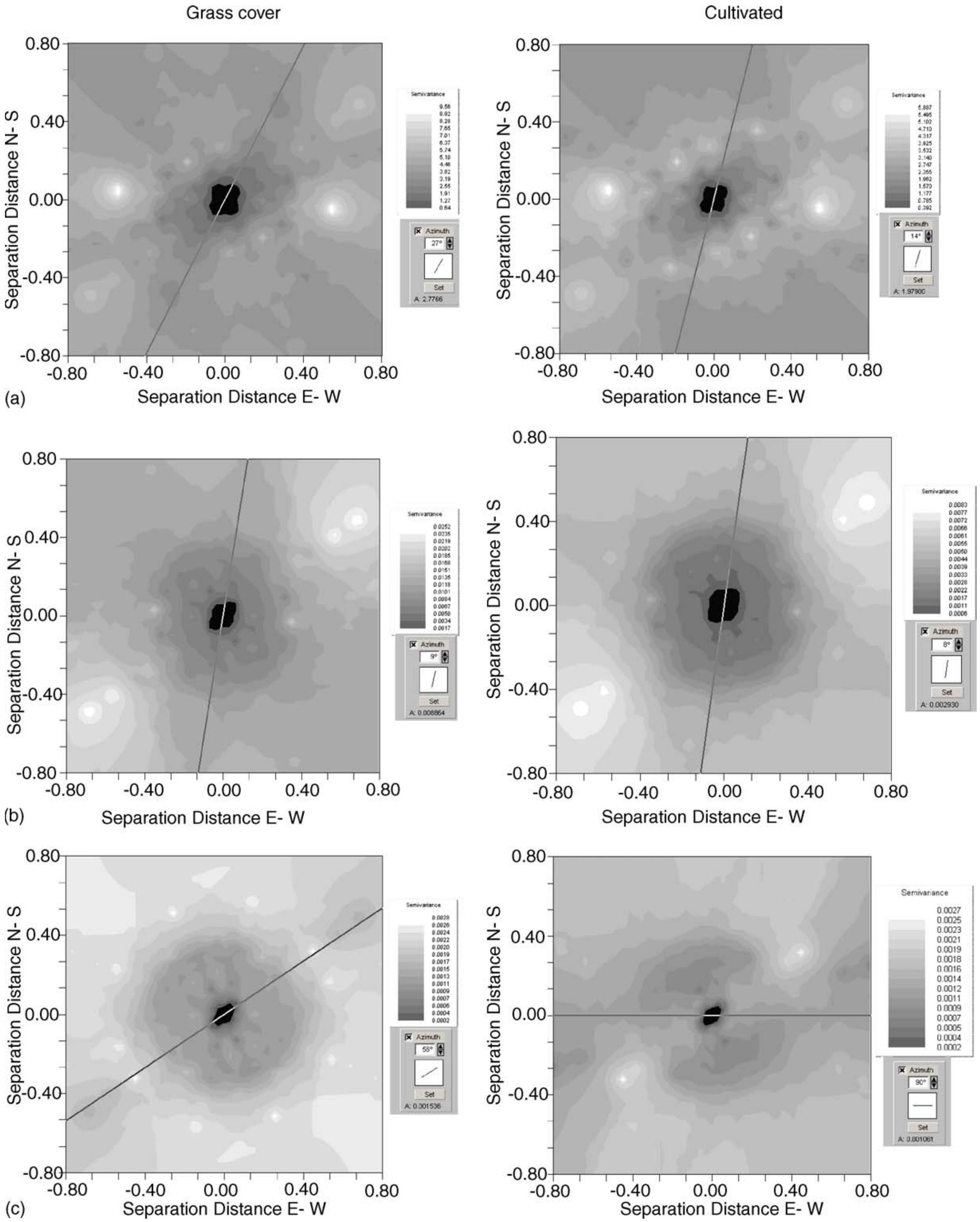

Fig. 4. Surface semivariograms: (a) penetration resistance; (b) bulk density; (c) water content.

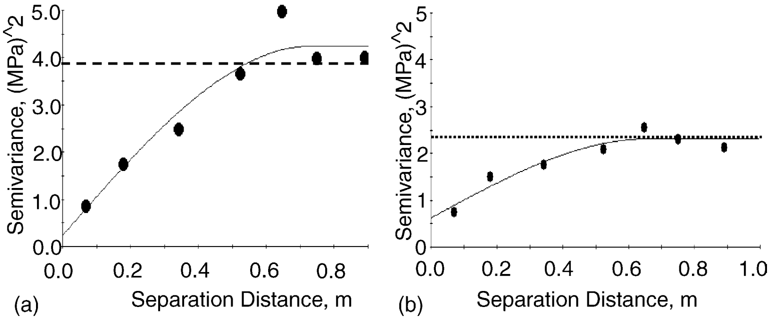

Fig. 5. Omnidirectional semivariograms of mean penetration resistance under G (a) and C (b).

resistance under G (0.91) than C (0.77). The proportion of the spatial structure for bulk density and water content under G was similar (0.88–0.89) and under C it was much higher for bulk density (0.99) and lower for water content (0.57). Much higher values of determination coefficient (R^2) for penetration resistance than bulk density and water content indicate that the former semivariogram model fits the experimental semivariogram data better. However, the values of reduced sums of squares (RSS) indicate higher differentiation between the model and experimental semivariograms under G than C for all properties.

The values of the soil properties can be affected by slope position, vine-rows and machinery traffic and therefore non-stationary conditions may occur. Taking this into consideration we performed an analysis of trend showing a linear trend of the data for all properties. A comparison of Tables 3 and 4 indicates that removing the trend caused decreasing nugget values to zero. The values of sill were decreased on average in both treatments by 1.4, 1.2 and 1.6 times for penetration resistance, bulk density and water content, respectively. The range for penetration resistance and bulk density was increased by 2.5

Table 3
Parameters of the mathematical variogram models under grass covered and conventionally cultivated soil

Properties[a]	Treatment	Model	Nugget C_0	Sill $C_0 + C_s$	Range A_0 (m)	Proportion $C_s/(C_0 + C_s)$	R^2	RSS
PR	Grass	Spherical	0.36	4.055	0.749	0.911	0.951	0.485
BD	Grass	Spherical	0.0015	0.0142	0.755	0.895	0.935	7.6×10^{-6}
WC	Grass	Spherical	0.00044	0.00245	0.803	0.882	0.759	8.7×10^{-7}
PR	Cultivated	Spherical	0.508	2.26	0.585	0.775	0.933	0.141
BD	Cultivated	Spherical	0.00001	0.00562	0.834	0.998	0.914	2.6×10^{-6}
WC	Cultivated	Exponential	0.001	0.00232	0.949	0.569	0.314	1.1×10^{-6}

[a] PR: penetration resistance; BD: bulk density; WC: water content; C_s: structural variance; R^2: determination coefficient; RSS: reduced sum of squares.

Table 4
Parameters of the mathematical variogram models under grass covered and conventionally cultivated soil without trend

Properties[a]	Treatment	Model	Nugget C_0	Sill $C_0 + C_s$	Range A_0 (m)	Anisotropy	
						Ratio	Angle
PR	Grass	Spherical	0	3.265	1.889	2	65.5
BD	Grass	Spherical	0	0.01007	1.182	1.557	58.9
WC	Grass	Spherical	0	0.001528	0.503	2	0.538
PR	Cultivated	Spherical	0	1.303	1.466	2	69.95
BD	Cultivated	Spherical	0	0.005	1.0	2	40
WC	Cultivated	Spherical	0	0.001388	0.5865	2	5.46

[a] PR: penetration resistance; BD: bulk density; WC: water content.

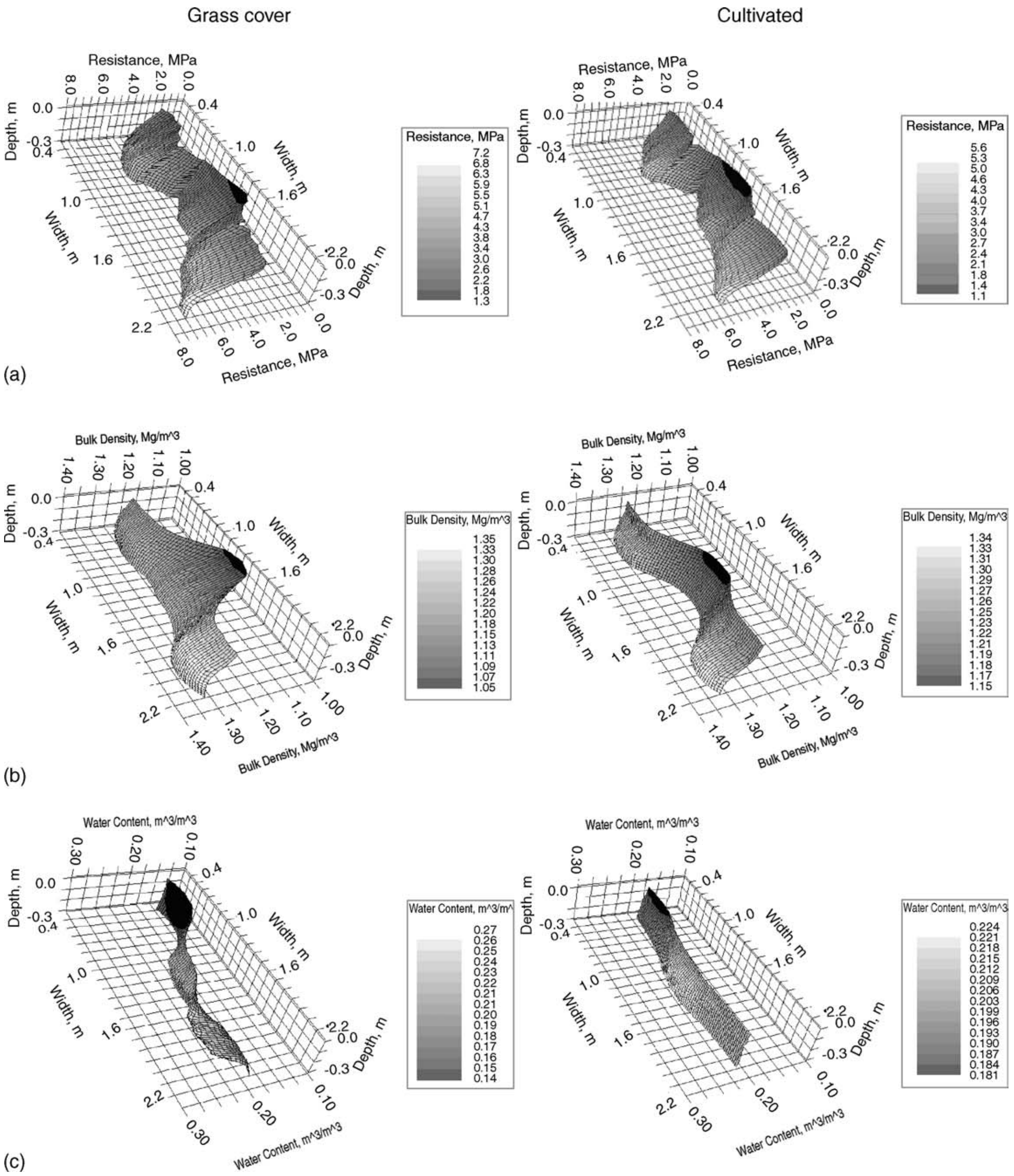

Fig. 6. 3D maps: (a) penetration resistance; (b) bulk density; (c) water content.

and 1.4 times, respectively and for water content it decreased by 1.6 times. The semivariance parameters indicate that removing of the linear trend improves the description of the variability of the studied properties. In addition, after removing the trend anisotropy of the penetration resistance and bulk density increased and that of water content decreased in grass covered and cultivated soil.

3.3. 3D maps

Fig. 6 presents the maps of penetration resistance, bulk density and volumetric water content obtained by ordinary block kriging using the semivariogram models. The areas of increased bulk density in the track ruts are clearly visible. As we expected the changes in bulk density were reflected in values of penetration resistance and similar distribution patterns of both characteristics (Fig. 6a and b). The relation between bulk density and penetration resistance was confirmed by significant correlation coefficients under G ($R = 0.581$) and C ($R = 0.493$) (Table 2). The effect of tractor traffic on both soil bulk density and penetration resistance was more pronounced under the lower ruts due to greater loading associated with the tractor's tilt and higher soil water content at traffic. Most pronounced strength levels were created in lower track below about 18 cm under both G and C. These results are consistent with earlier findings of Van Dijck and van Asch (2002) obtained in vineyards of Mediterranean France where soil compaction accumulated in deeper soil. The authors indicated that because of the light machinery used there was not a significant reduction in infiltration under natural rain events despite the formation of prismatic soil structure. The differences between the rut and inter-rut areas in our study were more pronounced under G than C, due to mostly greater penetration resistance under the tracks in G. Irrespective of the treatment, the differences in penetration resistance were relatively greater than those in bulk density. These confirm literature results indicating high sensitivity of penetration resistance to characterize soil management effects.

Volumetric soil water content under both treatments was higher in the lower ruts, and thus in the lower slope position than in the upper ruts (Fig. 6c). This could be enhanced by vine-row shadow in this vineyard of south/southwest aspect. Soil water content distribution with depth under upper rut in G was rather uniform. However, in inter-rut and lower rut areas down the slope, soil water content was greater, and, under the lower rut, more heterogeneous with depth. Under C the differences in water distribution between these areas were less pronounced. Fig. 6c also indicates that soil water content in the upper rut was lower under G than C, which can be associated with greater evapotranspiration in the former.

The 3D mapping of the inter-row allowed identifying the areas of highest soil strength in lower rut that corresponds to the upper side of the vine row and of lower strength corresponding to lower side of the same row in the sloping vineyard. This positional variation of the strength may result in different root growth and availability of water and nutrients. This result emphasizes the importance of site-specific management of fertilization in sloping vineyard to improve fertilizer-use efficiency (Choudhary and Prihar, 1974; Kaspar et al., 1991).

A comparison of Fig. 6a–c indicate that the distribution patterns of penetration resistance, bulk density and water content under both G and C are consistent with the distribution of upper rut, inter-rut and lower rut areas along the slope. But their interactive effects can be different depending on position within the inter-row. For example, irrespective of soil management, penetration resistance was greater in lower than upper crawler rut (Fig. 5a) despite higher water content which commonly decreases penetration resistance. This implies that increased soil water content under the lower crawler rut was not sufficient to offset the enhancing effect of soil compaction on penetration resistance. Greater penetration resistance under G than C at comparable depths and locations can be associated with lower soil water content under G due to depletion by roots and with greater internal soil strength induced by roots.

Results of the semivariance analysis without trend were used to create another set of 3D maps of the soil physical properties using ordinary kriging (Fig. 7). A comparison of Figs. 6 and 7 indicates that the values of the properties were somewhat higher without trend than those with trend. However, its detection is complex and time-consuming and therefore to make a decision to calculate the trend or not should depend on the required precision. Helpful prerequisites for such a decision could be provided by simple analysis of linear regression in two directions separately. If the regression coefficients are close to zero, the semivariance analysis can be done without removing trend.

High values of determination coefficients R^2 for both G (0.96) and C (0.95) indicate that created the 3D maps satisfactorily reflect real distribution patterns of the soil penetration resistance (Table 5). Less R^2

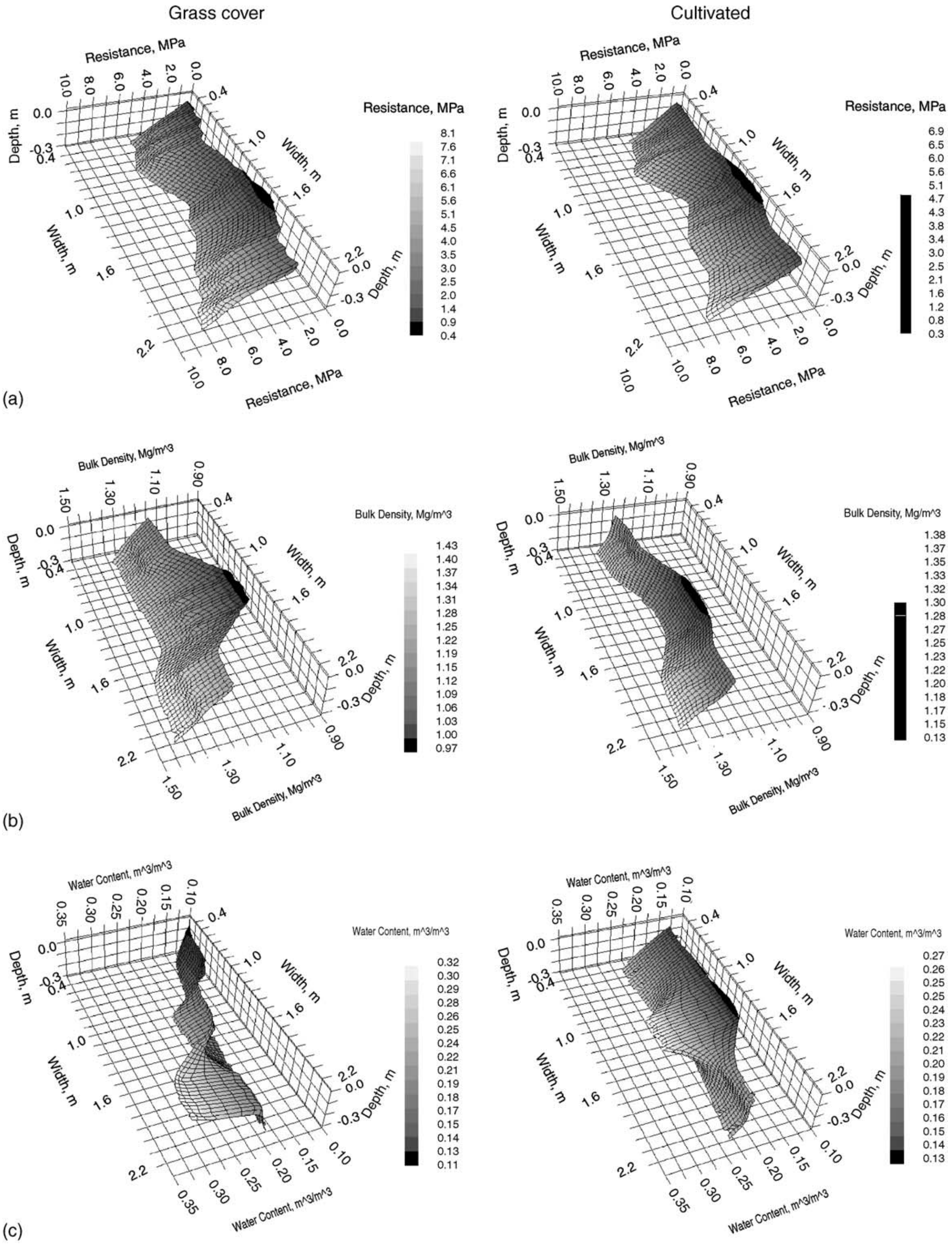

Fig. 7. 3D maps without trend: (a) penetration resistance; (b) bulk density; (c) water content.

Table 5
Validation parameters for soil bulk density, penetration resistance and water content under grass covered and conventionally cultivated soil

Treatment[a]	Regression coefficient	S.E.[a]	R^2	Intercept	SE prediction
Grass PR	1.0064	0.024	0.957	−0.26	−0.353
Grass BD	1.102	0.168	0.631	−0.13	0.057
Grass WC	1.006	0.157	0.621	−0.001	0.031
Cultivated PR	1.165	0.028	0.952	−0.446	0.293
Cultivated BD	1.086	0.121	0.762	−0.102	0.027
Cultivated WC	0.455	0.569	0.025	0.110	0.034

[a] SE: standard error; PR: penetration resistance; BD: bulk density; WC: water content.

values were obtained for bulk density under G (0.63) and C (0.76) and water content under G (0.62) and much less for water content under C (0.025). In most cases, linear regression coefficient (slope) was around one except water content under C (0.45). The lowest R^2 and regression coefficient values for water content under C indicate that the model poorly estimates its distribution in the soil profile.

The above interrelations of soil physical parameters indicate the usefulness of combined measurements in studying spatial and temporal variability of soil physical behavior as related to topsoil management, plant cover and slope aspect and position. New developments combining penetration resistance and water content sensors on the same measurement shaft (Young et al., 2000; Lowery and Morrison, 2002) allow minimization of complications due to soil heterogeneity and they reduce the disturbance of soil, and thereby increase efficiency of soil mapping.

4. Conclusions

We conclude that long-term tractor traffic across the sloping vineyard inter-row results in uneven spatial distribution of soil bulk density, penetration resistance and water content in grassed and cultivated vineyards. The highest variability was obtained for penetration resistance and the lowest for bulk density. The semivariograms used to characterize spatial variability of the characteristics were well described in most cases by spherical models. The ranges of spatial dependence were highest for soil water content and lowest for penetration resistance. The inverse was true after removing of the linear trend. In the case of penetration resistance the range was considerably greater under G than C with and without trend.

The 3D mapping allowed identify areas of high soil strength in lower crawler ruts (induced by tractor's tilt) corresponding to the upper side of vine row and of lower soil strength corresponding to other side of the same row down slope. This positional variation was more pronounced under G than C. Volumetric soil water content was lowest under upper rut and successively increased in inter-rut and lower rut areas. The values of all the soil properties were somewhat higher without trend than those with trend. As indicated by R^2 and regression coefficient values 3D maps well reflected spatial distribution of all parameters in both treatments except water content under C.

Knowledge on the spatial distribution of the trafficked vineyard inter-row can be used for development management options that minimize production risks and the harmful impact of traffic.

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