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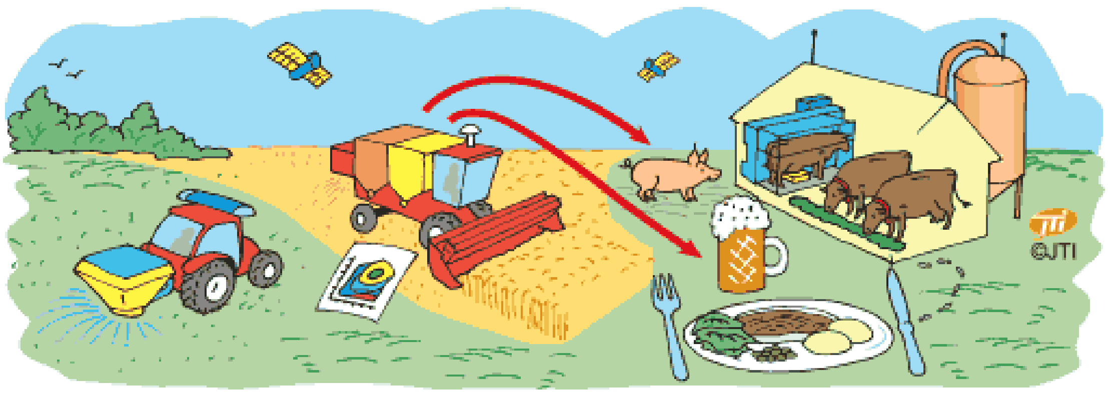

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Multivariate geostatistics for assessing and predicting soil compaction

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Abstract

The aim of this research is to investigate the potential of geostatistical techniques for understanding and evaluating the spatial variability of soil compaction, caused by the traffic of agricultural machines and/or the action of tillage implements.
Soil cone penetrometer resistance was measured in a field of inland Sicily, along a transect of 3 m length, from the soil surface until 70 cm depth.
The 3D mean maps showed a random variation on the surface and a high spatial correlation among penetrometer resistance data measured at different depths. The map corresponding to five tractor passes showed the largest extension of the areas characterised by the highest values of penetrometer resistance.
The probability maps showed that at least 20% of the monitored soil volume can exceed the critical penetrometer resistance for root growth.

Keywords: soil compaction, cone penetrometer resistance, multivariate geostatistics.

Introduction

The implementation of intensive agricultural production systems has led to use heavy machines with high working capacity and requiring high traction power. The traffic of these machines can cause soil compaction, a soil structure degradation reducing its porosity and creating obstacles to air, water and nutrient movement and root penetration (Heinonen et al., 2002, Hernanz & Sánchez-Girón, 2000, Febo & Pessina, 2002). In literature there are several examples concerning with the negative effect of soil compaction on crop production (Taylor et al., 1966). The measurement of cone penetrometer resistance is an empirical, easy, quick and cheap method, widely used for monitoring and assessing soil compaction (Pagliai et al., 2000).
The intensity and distribution of the traffic of agricultural machines and/or the action of tillage implements can cause a high variability of soil structure in the tilled layer, both vertically and horizontally (Castrignanò et al., 2001, Mouazen et al., 2001). One of the main causes of spatial variability of soil penetrometer resistance is wheeling, generating compacted soil volumes located under the wheel tracks (Richard et al., 1999), because it determines 3D variation patterns all over the field plots (Castrignanò et al., 2002a, Castrignanò et al., 2003). Therefore, it is needed to carry out the geo-referenced measurement of soil compaction and geostatistics provides different tools for joint analysis of the spatial and temporal variation of cone penetrometer resistance (Journel & Huijbregts, 1978). One approach consists in producing interpolated maps of cone penetrometer resistance over time using (co)kriging and, then, comparing each other, in order to detect persistence or changes in the spatial patterns over time (Goovaerts & Chiang, 1993, Castrignanò et al., 2002a). Another geostatistical modelling technique is

stochastic simulation, producing a set of alternative stochastic images of the random variable (Deutsch & Journel, 1998, Castrignanò et al., 2002b). The above techniques were mainly developed in order to adequately assess the spatial uncertainty.
The aim of this research is to investigate the potential of geostatistical techniques for understanding and evaluating the within-field spatial variability of soil compaction, caused by the traffic of agricultural machines and/or the action of tillage implements, and its temporal evolution, resulting from successive passes of a tractor.

Materials and methods

Materials for measuring geo-referenced soil cone penetrometer resistance

A system for the geo-referenced measurement of soil cone penetrometer resistance, mounted on a tracked minitransporter, Rotair Rampicar R-600, was used during the tests (Fig. 1).

Figure 1. The system for the geo-referenced measurement of soil cone penetrometer resistance used during the tests.

The instruments mounted on this minitransporter are:
- an electronic penetrometer, Eijkelkamp Penetrologger 06.15, constituted by an electronic force sensor with built-in depth ultrasonic sensor and data logger, a probing rod, ending with a cone of 5 cm^2 base area; this instrument has penetration force range of 0-1000 N, force resolution of 1 N, maximum depth of 80 cm, depth resolution of 1 cm, display of cone penetrometer resistance;

- a L1/L2 DGPS mobile receiver, Scorpio 6502 MK of DSNP (now Thales Navigation), connected to a data logger, Husky MP2500, and having a built-in UHF radio receiver, for receiving in real time the correction signals from a UHF radio transmitter, connected to a base station, Scorpio 6502 SK.

In order to lower or lift the penetrometer at a constant speed, the force sensor of the penetrometer was mounted on a hydraulic jack, which was fitted to a specifically built metal frame, jointed to the minitransporter. It is possible to set up the inclination of this frame, by the means of another hydraulic jack.

This system, requiring only one operator and able also to climb over sloping ground, has total mass of 400 kg, total contact surface of 0.288 m^2, soil ground pressure of 0.013 MPa, length of 1500 mm and width of 800 mm and, therefore, a small turning space. With respect to the manual penetrometers, this system allows to: highly decrease the measurement time; keep a constant penetration speed; apply a force normal to the field plane; correlate cone penetrometer resistance data with the related positions.

Methods for measuring geo-referenced soil cone penetrometer resistance

The measurement tests were carried out at the end of the crop season 2002-2003 in inland Sicily, in a field located at Alia (Palermo), on a sandy-silt soil (clay 8%, silt 33.7% and sand 58.3%).

Geo-referenced soil cone penetrometer resistance was measured along a transect of 3 m length, in points 7 cm far from each other, with a depth resolution of 1 cm, from the soil surface until 70 cm depth.

In order to study and evaluate the effects of the traffic of agricultural machines on soil compaction, the soil cone penetrometer resistance data were measured after none (P0), one (P1) and five (P5) passes of a four wheel drive tractor of 58 kW, FIAT 766 DT, with a mass of 3340 kg; its front axle was fitted with 13.6 R24 tyres and its rear axle with 16.9 R34 tyres; all tyres were inflated at 120 kPa.

During the tests the mobile receiver was used in the “stop-and-go” mode, in order to log real time differentially corrected positions, having an error of ± 1-2 cm.

The positions were processed using the Kinematic Interface Survey Software (KISS), while the cone penetrometer resistance data measured in each point were processed and displayed using the Eijkelkamp PenViewer software.

Techniques of multivariate geostatistics

A multivariate geostatistical approach was applied for analysing the space-time behaviour of penetrometer resistance data. A multivariate Gaussian simulation approach (Castrignanò et al., 2002b) has been applied to cone penetrometer resistance data, measured after none, one and five passes of the tractor. The raw distributions were transformed into the normal ones by fitting a transformation function, called the Gaussian anamorphosis. The simulations were generated using the conditional sequential Gaussian simulation algorithm (Deutsch & Journel, 1998). Probabilistic information was extracted from this set of simulated images: 1) averaging the simulated values for each pixel and producing the map of the value “expected” at any considered position (E-type or Expected-value estimate) (Journel, 1983) and 2) the map of the related standard deviation; 3) counting the number of times that each pixel exceeds a critical threshold value and converting the sum to a proportion, in order to produce a probability map.

Results and discussion

The descriptive statistics of the cone penetrometer resistance data measured along the transect after successive tractor passes are shown in Table 1.
The soil cone penetrometer resistance resulted spatially variable from 0.09 to 5.50 MPa, which was the upper limit of the penetrometer pressure range. The mean values were affected by the machine traffic, reaching the maximum value after five tractor passes. Also the spatial variance followed the same temporal pattern, even if the differences were less sensitive to the machine traffic. The χ^2 test for normality was rejected for P0, P1 and P5 distributions, as it is also proved by the large positive values of the skewness parameter and the smaller median values compared with the means. The kurtosis parameter showed a significant shifting from normality (value 3) only for the P5 distribution.

Table 1. Basic statistics of soil cone penetrometer resistance (MPa) measured after none (P0), one (P1) and five (P5) passes of the tractor.

Variable	Count	Minimum	Maximum	Mean	Median	Std. Dev.	Variance	Skewness	Kurtosis
P0	2378	0.090	5.50	1.93	1.61	1.57	2.45	0.95	3.05
P1	2098	0.10	5.50	1.88	1.50	1.52	2.31	1.11	3.37
P5	2238	0.15	3.960	2.40	1.950	1.69	2.86	0.64	2.30

In order to discover some temporal trend in soil cone penetrometer resistance as an effect of the tractor traffic, the correlation coefficient between the measured data related to P0, P1 and P5 distributions was computed (Table 2). The correlations were always significant and tended to slightly increase as the number of the tractor passes increased; this demonstrates that the soil kept well structured at least within five tractor passes.

Table 2. Correlation matrix between soil cone penetrometer resistance values measured after different passes of the tractor.

Variable	P0	P1	P5
P0	1.000	0.560	0.632
P1		1.000	0.64
P5			1.000

However, the values of soil properties which are measured close to each other are frequently more similar rather than the values measured further apart. Therefore, the spatial dependence was taken into account, by computing the experimental simple and cross-variograms of the normal scores of the cone penetrometer resistance data measured in the same points in correspondence of the successive tractor passes. In order to discover some spatial anisotropies, all the simple and cross-variograms were computed in the three main space directions: the first two directions (longitude and latitude), belonging to the reference plane and the third direction orthogonal to the reference plane. Because all the measured data were within a narrow band including the transect, whose direction mostly coincided with the longitude axis, an isotropic variogram on the reference plane was computed.

Then, a linear model of coregionalisation was fitted to all these variograms in a semi-automatic way: only the final tuning of the corresponding sills was automatically performed but the number, type, range and anisotropy of the basic spatial structures were chosen.
Three basic structures were used:

1) isotropic spherical model on the reference plane with range of 0.50 m;
2) directional cubic model with range of 0.20 m along the axis orthogonal to the reference plane;
3) Bessel-k model (Geovariances, 2004) with scale of 1.00 m and parameter equal to 1 along the axis orthogonal to the reference plane.

The multivariate model is presented in Table 3, where the coregionalisation matrix is shown for each of the three basic structures, together with the corresponding Eigen values. As it is demonstrated by the Eigen values, most of spatial variability is evident along the axis orthogonal to the reference plane at longer range. Moreover, at this spatial scale the three penetrometer resistance data sets resulted highly correlated, because the first Eigen value explained more than 97% of the spatial variance corresponding to that basic structure.

Table 3. Fitted linear model of coregionalisation of the normal scores of the corresponding soil penetrometer resistance variables (G0, G1, G5). The coregionalisation matrices related to the three basic structures and the corresponding Eigen values and the variance percentage (within parenthesis) are reported.

Model	Variable	G0	G1	GP5	Eigen.1	Eigen.2	Eigen.3
Isotropic spherical	G0	0.5729	0.0972	-0.0155	0.6256 (44.16%)	0.4344 (30.67%)	0.3566 (25.17%)
	G1	0.0972	0.4463	0.0358			
	G5	-0.0155	0.0358	0.03974			
Directional cubic	G0	0.4556	0.13267	0.1318	0.5465 (74.26%)	0.1443 (19.60%)	0.0452 (6.14%)
	G1	0.1326	0.0947	0.0170			
	G5	0.1318	0.0170	0.1856			
Directional Bessel-K	G0	2.3105	4.1764	3.7675	16.3079 (97.51%)	0.4171 (2.49%)	0.00 (0%)
	G1	4.1764	7.5499	6.8333			
	G5	3.7675	6.8333	6.8646			

If the diagonal terms (variances) of the three coregionalisation matrices are considered, it is possible to observe that as regards the shorter range variation (both on the reference plane and along the axis orthogonal to the reference plane) P0 shows the highest variance; on the contrary, along the axis orthogonal to the reference plane at longer range P1 and P5 show the greatest variances. This may be interpreted as a progressive soil stratification caused by the successive passes of the tractor.
The Figure 2 was produced by jointly processing the set of the co-simulated images of the three back-transformed variables: the mean of the 500 simulations produced at each grid node was computed and, then, the results for each variable were displayed in 3D maps. Because of the geometry of the considered volume, the latitude axis was distorted by a factor of 10 with respect to the reference plane, in order that the maps can be more easily read.

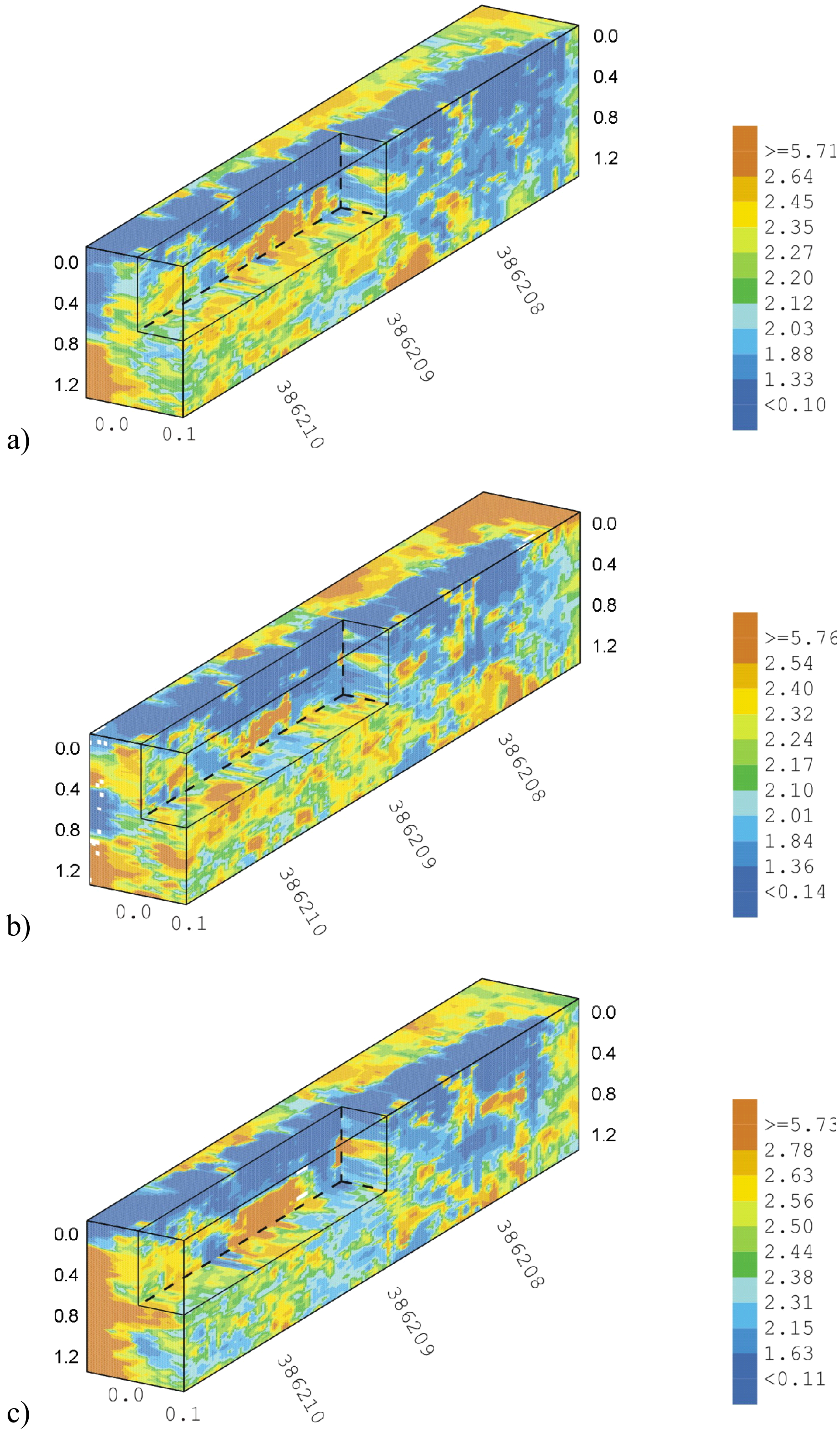
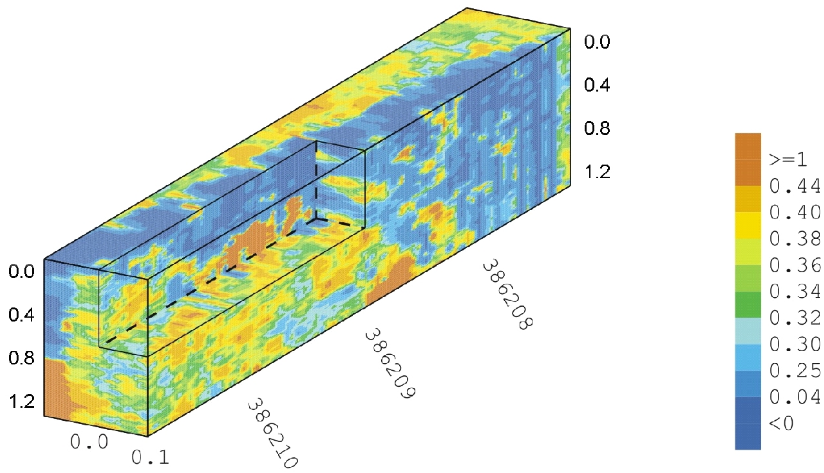


Figure 2. 3D mean maps of soil cone penetrometer resistance (MPa) related to none (a), one (b) and five (c) passes of the tractor.

The 3D mean maps show that most variations were of erratic type, with a slight stratification along the axis orthogonal to the reference plane. The above results also show some anisotropy between the east half of the considered volume and the west one, generally characterised by higher values of cone penetrometer resistance. The persistence of a compacted zone at a depth equal or less than 40 cm is also evident, probably due to the traditional tillage made every year at the same depth. Therefore, more conservative practices should be encouraged in soil management. The three maps do not show significant differences among each other but a larger extension of the areas characterised by the highest values of soil penetrometer resistance can be detected in the latest map.

In order to quantify the compaction risk in probabilistic terms it is possible to compute the probability of exceeding a certain threshold of soil cone penetrometer resistance. The probability maps, corresponding to the successive tractor passes and obtained by post-processing the 500 co-simulated images of penetrometer resistance data, are shown in Figure 3. In our research the threshold value was 2.5 MPa, considered as a critical value for root growth (Taylor et al., 1966).

If a probability level (for example 0.4) is considered, it is possible to observe the areas where the probability of exceeding the threshold value is higher than the assumed probability level. In Figure 3 the areas at compaction risk are mostly located in the west half and approximately below 30-40 cm depth. Having used the decile classes for the colour scale, it is possible to deduce that after none and one pass of the tractor the soil volume at compaction risk was about 20% and this value increased up to about 40% after five passes. The main difficulty met in this approach consists in appropriately choosing a probability level above which it is needed to plan some remediation actions.



a)

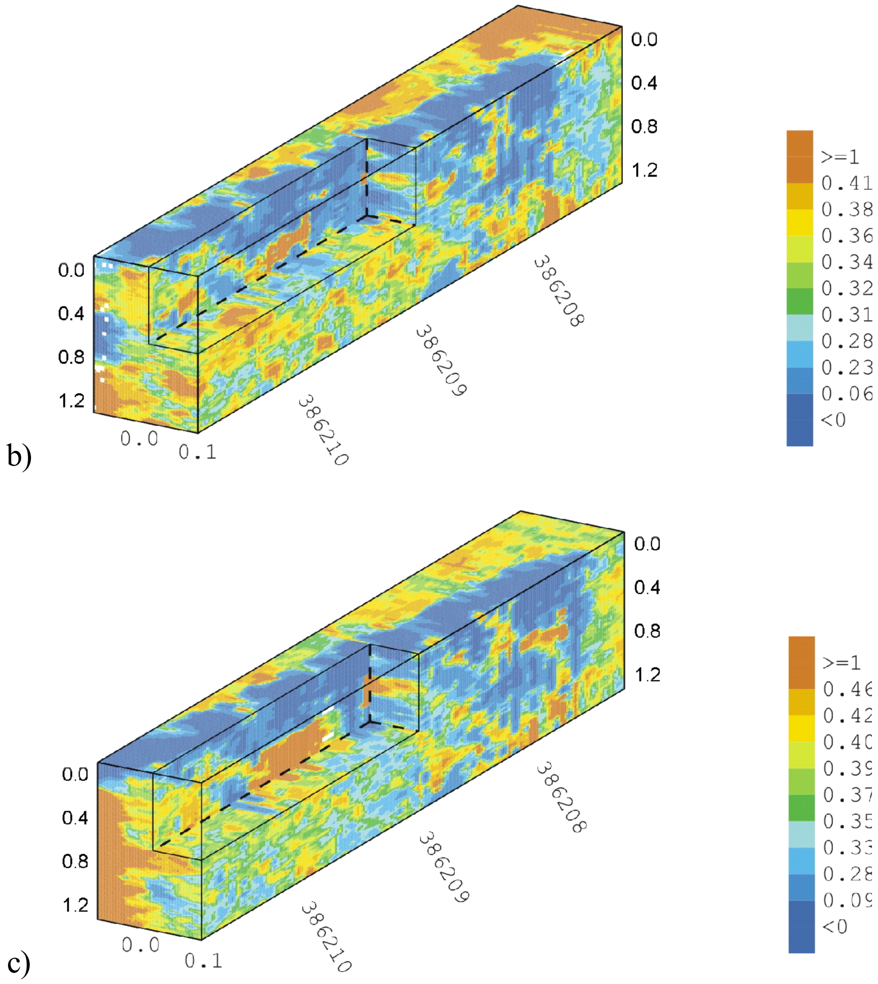


Figure 3. 3D probability maps of exceeding the threshold of soil cone penetrometer resistance related to none (a), one (b) and five passes (c) of the tractor.

Conclusions

This research showed the potential negative effects of the traffic of agricultural machines and conventional tillage practices, based on mouldboard, on the soil structure. Geostatistical techniques, applied to penetrometer resistance data, can be an useful tool for better understanding and evaluating the within-field spatial variability of soil compaction and also spatial co-variation of soil physical properties and crop yield. Thus, the traffic of agricultural machines for the next cultivation can be better planned and better recommendations can be made about spatially variable field management.

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