3D SPATIAL VARIATION OF SOIL IMPEDANCE AS AFFECTED BY SOIL TILLAGE

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Abstract
Soil impedance, measured with a cone penetrometer, represents a very quick and simple measurement, but its interpretation is quite difficult because soil impedance depends on many other soil properties. Moreover, the measure is essentially punctual, with very high spatial and temporal variability. Therefore, there is a need to define a proper methodology of processing impedance data, in order to separate soil characteristics effects from tillage effects. In this paper a methodological approach is proposed for the measurement, analysis and processing of cone penetrometer data, in order to assess the effects of tillage treatment, position and depth on soil impedance. Cone resistance measurements were made according to a regular grid at the nodes of 6 m x 3.5 m cells to a depth of 50 cm with vertical increments of 3.5 cm, in a field cropped with sugar beet during one crop season. At each sampling date, some days after irrigation, cone resistance data were collected and interpolated using geostatistical techniques to produce three dimensional maps. Cone resistance showed mostly random variations on the horizontal surface, whereas it revealed the persistence of a compacted zone at variable depth. The intrinsic soil variation related to position, depth, soil water content and tillage depth were the main factors causing soil impedance to change.

Additional Keywords: spatial variation, soil tillage, cone penetrometer, compaction, 3D mapping.

Introduction
Conventional agriculture is mainly characterised by deep and intensive tillage, which can cause soil degradation through loss of organic matter, soil erosion and compaction. On the silty-clayey soils and in drought conditions, typical of the Tavoliere Plain in southern Italy, compaction pans produced by tillage may be a yield-limiting factor. These soils have typically been producing durum wheat under a mono-crop production system over several years, using intensive deep tillage to control weeds, prepare seedbeds and incorporate fertilisers and herbicides. Although these soils are highly productive and classified as Vertisols, the combination of intensive tillage and mono-crop culture has contributed to plow pan formation in many fields. However, most of farmers do not know the extent and severity of soil compaction within their fields and then cannot plan effective procedures of remediation. One way of testing soil compaction is recording mechanical impedance with a cone resistance (Castrignanò *et al.*, 2002; 2003), which is an empirical, easy and cheap measurement, widely used to assess the effects of soil tillage. However, the complex interaction between cone resistance and several soil properties often causes fluctuations and difficulties in data interpretation (O'Sullivan *et al.*, 1987). Classic statistical methods have generally been used in the past to study soil variability in the field, but they assume all variability is random. Soil characteristics generally show spatial dependence (Webster and Oliver, 2001), which means that samples close to each other are more similar than samples further from each other. Classical statistics is then not suited to analyse spatially dependent variables, such as soil impedance, because it assumes that measured data are independent. Spatial variability of soil properties is mostly studied by using geostatistical methods, which take into account spatial autocorrelation of a variable in predicting its value in an unsampled location.

Soils are three dimensional bodies with properties than can vary over different spatial and temporal scales in every direction. Nevertheless, soils are generally investigated only in horizontal dimensions and if 3-D characterisation of spatial variability is the aim of survey, they are mapped as a set of horizontal layers for a number of depths. The main drawback of this layered 2-D approach is that discrepancies may occur between these layers when they are put one on top of the other. This is a great disadvantage, especially when a 3-D model of soil is required in crop growth simulation. There are no many 3-D studies in soil science (Van Meirvenne, *et al.*, 2003; Castrignanò *et al*., 2002; 2003). The 3-D approach should be the proper approach to investigate the continuity of plow pan in both horizontal and vertical dimensions. The objectives of this study were to observe the formation of a plow pan and describe its 3-D variability in the study area, submitted to different soil tillage treatments.

Materials and Methods
Experimental site and field measurements
The study was conducted on a two-year durum wheat - sugar beet rotation in the experimental farm of the Agronomic Experimental Institute during the 2001 crop season of sugar beet. The farm is situated in the outskirts of Foggia (41° 27' N, 15° 36' E, 90 m a. s. l.), on the flat land of southern Italy. The soil is a deep, silty-clay

Vertisol of alluvial origin, classified as fine, mesic, Typic Chromoxerert in USDA Soil Taxonomy. The climate is characterised by hot and dry summers with rain concentrated mainly in the winter months. The rainfall received during the months of March, April and May, did not meet the sugar beet's water requirements, so water was applied to the plants in order to prevent water stress during the long dry spell from June to August.

A 200 m by 80 m experimental field was differently managed in soil tillage on plots of 900 m^2 and the treatments consisted of four different systems: A - conventional (double-share ploughing at 35-cm depth, two rotary tillage applications at 20-cm depth with disc plough + 10-cm rotary tillage); B - two-layer (combined equipment - 50-cm sub soiling + 10-cm rotary tillage); C - surface (20-cm five-share ploughing + 10-cm rotary tillage); D - minimum (10-cm rotary tillage). The tillage treatments were randomly assigned to the whole plots in three blocks. Sugar beet (cv. Puma) was sown on March 5th following the durum wheat cultivation.

Soil strength was measured using a Bush recording soil penetrometer (Findlay, Irvine) with a 30°-angle and 12.83 mm-diameter cone, corresponding to the American Society of Agricultural Engineering standard (ASAE, 1993). The penetrometer resistance measurements were made by grid profiling with approximately regular cells of 6 m by 3.5 m. At each grid node, soil resistance was recorded at 3.5-cm depth increments up to the total length of 52.5 cm and stored on a data logger unit. The soil penetration resistance was measured on two occasions; June 17th and July 17th 2001; approximately one week after watering. At each recording date, gravimetric soil water content was measured from sampling the depths of 0 to 0.20, 0.20 to 0.40 and 0.40 to 0.60 m at the nodes of a coarser grid for a total of 72 locations.

Geostatistical analysis

To describe the significant amount of soil impedance variability through both space and time, the approach, based on stochastic models and involving extension of geostatistical analysis tools to include the additional time dimension, was used. According to this method, the set of T sampled times is viewed as a realisation of T random functions. The estimation of the property of interest involves fitting a linear nested model to the simple variogram, which consists of expressing the variogram as linear combination of some basic structures. In the situation where spatial variability is different in different orientations, directional variograms must be calculated producing an anisotropic variogram model. As the variable was spatially sampled in 3-D, modelling a 3-D directional variogram was required. For this we followed the approach presented by Armstrong (1998), which consists in modelling the directional variograms by considering only pairs located in the horizontal plane or in the vertical direction and then combining these directional variograms into one 3-D model. Finally, the two temporal measurements of soil impedance were estimated through kriging at the nodes of a dense 3-D interpolation grid. The soil water contents at the three soil layers were estimated at the nodes of a 2-D grid by a 2-D cokriging, after modelling of a linear variogram model (LCM) where all the simple and cross-variograms were represented as linear combinations of the same basic structures (Castrignanò *et al.*, 2003).

Results and Discussion

Basic statistical properties of the penetrometer measurements, made within the field on the two dates, are reported in Table 1. On the July date the penetrometer values were characterised by a wider range of variation and by a greater mean, as a consequence of the drier soil conditions owing to the higher evapotranspiration. On both dates

Table 1. Basic statistics of soil strength (MPa) measured on the different dates

SOIL STRENGTH (MPa)	Date	
	06/17/2001	07/17/2001
Minimum	1.029	0.648
Maxium	2.756	4.267
Mean	1.786	2.297
Std. Dev.	0.349	0.637
Variance	0.122	0.406
Skewness	0.101	0.298
Kurtosis	2.448	3.139
Variat. Coef.	0.196	0.277
Median val.	1.778	2.223

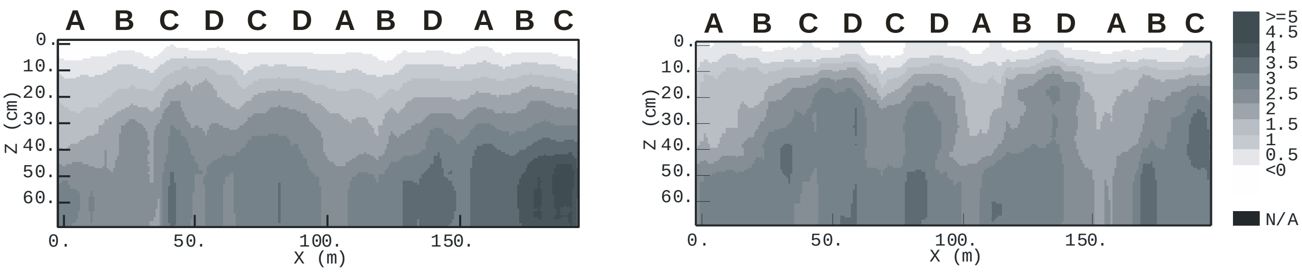
the distributions of soil impedance were very close to normal, as illustrated by the skewness near zero and by the small differences between the mean and the median values. Only the other shape parameter (kurtosis) showed some shifting from normality (value = 3).

The spatial-temporal dependence was assessed by fitting a directional linear model to the two penetrometer data sets recorded on the two dates to match the observed spatial anisotropies. The simple variograms were split into two types: those belonging to the horizontal reference plane and the variograms normal to this plane. Four basic spatial structures were used for the fitted variogram model for both dates: (1) nugget effect (0.045); (2) spherical model with range of 10 m on the horizontal plane (0.132); (3) spherical model with range of 50 on the horizontal plane (0.072); (4) cubic model with range = 2 m in the direction normal to the horizontal plane (11.700), for the earlier date and (1) nugget effect (0.147); (2) omnidiretional spherical model with range of 8 m (0.045); (3) spherical model with range of 19.97 m on the horizontal plane (0.025); (4) spherical model with range = 1 m in the direction normal to the horizontal plane (0.380), for the later date (inside the parentheses the sills are reported).

The choice of these spatial structures was suggested by the particular behaviour of the directional experimental variograms (not shown), that showed the following characteristics: 1) the simple horizontal variograms increased very quickly within a given distance (50 m for the June date and 19.97 m for the July date) till to reach a constant sill, much below the dispersion variance; 2) vertical variograms increased quite sharply and monotonically without reaching any sill, at least within the surveyed soil depth. The vertical variation is assumed to be stationary within 2 m for the earlier date and 1 m for the later one. As it can be derived from the structural analysis, the behaviour of the soil impedance was quite different on the two dates. In June the variation was mostly along the vertical direction, whereas the variation on the horizontal plane was split into two components: one at short-range (< 10 m), which was predominant, and the other one at long-range (< 50 m) less relevant. In July most of variation occurred along the vertical direction, but the spatial heterogeneity was essentially random on the surface.

A probable explanation of these differences on the two dates may be the different water content in the soil, which was drier at all depths in June than in July. The cokriged maps (not shown), obtained after fitting a LCM to the 6 soil water contents relative to each depth and date. The above model includes two spatial structures: (1) a cubic model with range of 19 m and (2) a spherical model with range of 100 m. Spatial soil water variation reproduces the separation of the plots along the y-direction, however, no significant difference among the differentially managed field strips was observed. The soil profile looked more homogeneous in June, whereas the 40-cm surface layer was drier in depth in July. This increase of spatial variation, mainly along the vertical direction, revealed a transient state in soil moistening owing to the high evapotranspiration.

Though quite informative, the previous variography analysis of soil impedance cannot locate the eventual presence of compaction and ascertain if the formation of an impervious layer is affected by different soil management. Therefore, to evaluate the extent of the horizontal and vertical variations of soil impedance and show if it is affected by different tillage depth, cone index data were interpolated by kriging according to a 1 m x 1 m x 0.01-m grid cell for a total of 454329 3D-grid nodes at each recording time. Since most of spatial variance was concentrated along the soil profile, we chose to visualise the results by using vertical sections of the surveyed depth on the different dates (Figure 1). A clear stratification was evident with a general increase of cone resistance with depth, which may confound the tillage effects over time. In June the threshold of 2 MPa, that it assumed as a critical value for root penetration (Taylor *et al.*, 1966), was generally reached at depth deeper than 40 cm. In July

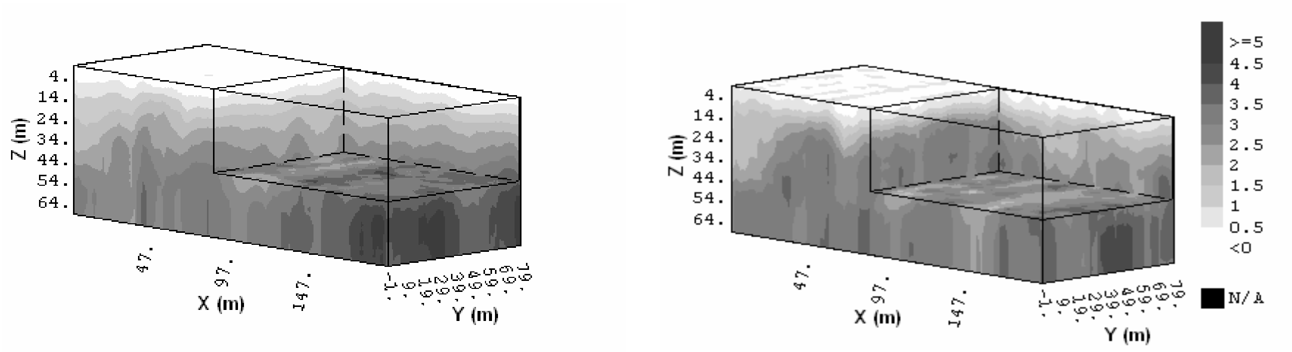


(T1) ***(T2)***

Figure 1. Vertical sections of cone penetrometer resistance in MPa on the different dates; June 17th *(T1)*; July 17th *(T2)*

the impervious layer rose up to shallower depths, reaching depths less than 20 cm at some points. However, this layer kept its depth at about 40 cm in the plots traditionally treated with ploughing or sub-soiling.

To produce a more global description of spatial variability of soil impedance, the results of kriging estimation in 3D grids were visualised by using the Excavated Box option in ISATIS software, which consists in penetrating into the soil and digging a portion of the grid. Figure 2 shows the estimated soil impedance in 3D maps, one for each recording date. The 3D maps show a greater homogeneity of soil impedance on the X-Y sections compared with the variability along the vertical profile. On the earlier date of measurement soil was characterised by impedance values greater than 2 MPa on average at depths deeper than 40-45 cm. At this time the soil did not seem to be significantly affected by the differentiation in tillage. A different behaviour can be observed for the map relative to later date, because the critical threshold of 2 MPa was reached at depths less than 20 cm in correspondence of the more superficially tilled strips. For the deeply managed plots the depth of the impervious layer changed but only at a less extension owing to increased soil drought.



(T1) ***(T2)***

Figure 2. 3D maps of soil strength relative to the different dates; June 17th *(T1)*; July 17th *(T2)*

These results confirm the influence of tillage depth in creating good conditions for roots growth and development, in terms of porosity and penetrability. Compaction of subsoil reduces water and air inflow into subsurface layers, so causing a decrease of roots growth and then a reduction in production. Therefore, soil tillage was traditionally aimed at improving subsoiling conditions through deep ploughing; however, it can cause soil structure degradation, whose immediate consequences are: decreased water and fertilizer efficiencies and increased soil erosion. The results of this study showed that the plow pan occurred at a depth variable as a function of soil water content and tillage, as continuous tillage at the same depth resulted in the formation of compaction below the tillage depth.

Conclusions

The purpose of this paper was to assess and describe the spatial variation of the field-measured values of cone index on two occasions during the growing season of sugar beet on areas submitted to different tillage treatments. Geostatistical models have been applied for modelling spatiotemporal distributions of soil impedance, which was visualised on a 3D graph.

This study was very useful in understanding the spatial variability of the soil submitted to different tillage treatments and revealed the general persistence of soil compaction associated to the surface till. These results are important also for the implications in site-specific management, because the plow pan can be alleviated by varying the depth of tillage over space and time and/or by more conservative practices. Soil compaction is a human-induced problem, which can be prevented through better soil practices that do not disrupt natural soil architecture and protect biological activity improving soil structure, porosity and quality for crop production.

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