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A combined geophysical-pedological approach for precision viticulture in the Chianti hills

E. Martini[1], C. Comina[2], S. Priori[3] and E.A.C. Costantini[3]

[1] *UFZ – Helmholtz Centre for Environmental Research, Leipzig, Germany*
[2] *Department of Earth Science, Università degli Studi di Torino, Italy*
[3] *CRA - ABP, Research Centre for Agrobiology and Pedology, Firenze, Italy*

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ABSTRACT The aim of the present work was to test and develop a combination of both geophysical and pedological survey techniques devoted to the definition of a correct plan for precision viticulture. In particular, the objective of the study was to evaluate the potentiality of a combined use of these techniques to identify areas with uniform soil properties within 4 test vineyards of the "Barone Ricasoli" farm, located in the Chianti wine district (Tuscany, central Italy) and to evaluate the relationships between soil properties and wine quality. Two different geophysical methods based on the measurement of the electrical conductivity were used: an electro-magnetic induction method and electric resistivity tomographies; these were combined with detailed pedological analyses and with the evaluation of remote sensing maps. All results were compared and discussed, and finally a cluster analysis based on the evidences of geophysical tests and on pedological data was performed. For each of the identified uniform areas, a separate winemaking was successively made, and the quality of the wines is discussed and correlated to the geophysical-pedological results. The study has shown that the approach used is suitable for mapping and understanding the anomalies in soil distribution which partially reflects in the quality and effectiveness of wine production. Moreover, it was demonstrated that the geophysical data alone are not able to provide any pedological information because, in the investigated area, electrical conductivity is affected by various soil properties in a complex manner; however, these methods are very useful to integrate and complement pedological data in the aims of precision viticulture.

Key words: EMI sensors, geophysics, soil science, apparent electrical conductivity, precision viticulture.

1. Introduction

Precision agriculture is a growing discipline combining geospatial data sets, state-of-the-art farm equipment technology, GIS, and GPS receivers to support spatially variable field application of fertilizer, soil amendments, pesticides, and tillage effort (Morgan and Ess, 1997). This approach overcomes the paradigm of uniform field treatment by site-specific data acquisition to cope with within-field variability. The benefits of precision agriculture to farmers are maximized crop yields and reduced input costs, allowing a farm field to be divided into different management zones for the overall purpose of optimizing economic benefits and environmental protection. Recent research on precision viticulture has focused on the use of management zones, which are defined as subfield regions within which the effects on the crop of seasonal differences in weather, soil, management, etc. are expected to be uniform (Lark, 1998). For this purpose, it is often useful to define classes from a set of multivariate spatial data. Cluster analysis procedures have been effectively used to divide a field into potential management zones (Stafford *et al.*, 1998).

During the last years, some important farms have adopted precision viticulture to optimize vineyard performance according to grape yield, wine quality, and sustainability of the natural resources (Proffitt *et al.*, 2006). The adoption of precision viticulture requires the knowledge of soil spatial variability in terms of physical, chemical and hydrological properties, which are functional to wine management. The farmer needs geo-referenced maps, displaying areas with similar soil characteristics and qualities like soil texture and drainage, which are related to soil water availability.

Traditional soil surveys and soil analysis are usually time-consuming and expensive, especially for high resolution maps. In the last two decades, after the maturation of GPS and GIS techniques, many technological tools were however developed to improve the spatial and temporal information about soil nutrient and water content. Development in soil spatial information technology such as proximal sensing has been continuously improved and applied in many studies (Corwin and Lesch, 2005). In this context, geophysical methods offer a valuable mean to obtain subsidiary data in an efficient way, and have been widely applied in soil sciences for a considerable period of time (Samouëlian *et al.*, 2005). In particular, geoelectrical soil mapping has become widely accepted in precision farming. At present it is the most successful geophysical method providing the spatial distribution of relevant agronomic information that enables to determine management zones for precision farming (Lück *et al.*, 2009). Methods based on the electrical properties demonstrated particularly promising because important soil physical properties are strongly correlated to electrical conductivity and can be potentially quantified indirectly from this parameter. For this reason a rapid, non-invasive and relatively cheap mapping of the soil apparent electric conductivity (ECa), e.g., carried out by Electro-Magnetic Induction (EMI) sensors, represents a very useful tool for identifying soil map units and soil properties in respect to clay content (Morari *et al.*, 2009), soil depth (Saey *et al.*, 2009), water content (Davies, 2004; Cousin *et al.*, 2009; Lück *et al.*, 2009; Tromp-van Meerveld and McDonnell, 2009) and water salinity (Doolittle *et al.*, 2001). The same technology was used to upgrade existing soil maps and to support the hydropedological model of a certain area (Indorante *et al.*, 2008; Costantini *et al.*, 2009; Tromp-van Meerveld and McDonnell, 2009).

Although the variations in EMI response are usually driven by the dominant soil property, the ECa can be affected in a complex manner by a number of different soil properties at the same time; therefore, a limited soil sampling and analysis program is typically required to determine which soil properties have the greatest influence on the ECa spatial variability. Soil properties information based on ECa measurement is needed for planning management practices; on top of that, since the spatial pattern of crop yield commonly exhibits a strong correlation with the spatial ECa pattern, it follows that ECa maps drawn by resistivity and electromagnetic induction surveys can be a valuable precision agriculture tool, providing insight on how to best divide a field into zones based on soil property differences (Allred *et al.*, 2006). Furthermore, the mapped horizontal ECa patterns for a farm field often tend to remain consistent over time, which implies that the ECa pattern is mainly governed by lateral variations in soil properties (Lund *et al.*, 1999; Allred *et al.*, 2005, 2006) and not by temporary variations in soil water content. To improve the characterisation of single soil profiles, the EMI method can be coupled with electrical resistivity tomographies (ERT) to increase the vertical resolution of subsurface electrical images (Rizzo *et al.*, 2004), and better understand the overlying geology on which the shallowest soil has been developed.

The goal of this work was, therefore, to test and develop a combination of survey techniques based on geophysical, pedological and remote sensing methods, allowing the application of a correct plan for precision viticulture. In particular, the objective of the study was to identify, within the test vineyards, smaller areas with uniform soil properties. Secondary objective of the study was to test geophysical methods to identify the drainage paths and, more in general, to prove the suitability of different techniques for detailed soil mapping.

2. Materials and methods

The studied area is described in the following paragraphs together with a discussion of the geophysical and pedological surveys. The central part of the work consisted in monitoring the experimental vineyards using an EMI instrument able to measure, at the same time, the ECa of soil at two depths. Moreover, to investigate some spots of particular interest, identified on the basis of the horizontal ECa distribution, ERT were also performed. These geophysical surveys were combined with pedological analyses on several soil samples.

At a final stage a cluster analysis to evaluate the correlation between wine quality and soil features detected by pedological and geophysical methods was attempted. On the sub-areas selected by the analysis, separate wine making was conducted and the resulting quality of the wines analyzed.

2.1. Study site and soil map

The four studied vineyards (17.6 ha in size, in total) were located inside the “Barone Ricasoli” farm, one of the most important winery of the “Chianti Classico” wine district area (central Italy). This territory is placed in the central-western part of Tuscany, between the cities of Firenze, Siena and Arezzo (Fig. 1).

The vineyards are placed on variable morphological conditions with moderate inclination, from 5 to 15%, showing variable exposition. Geological and pedological characteristics of the vineyard are very heterogeneous and are made even more complex by the vineyard ground preparation, land leveling, deep ploughing, setting of drainage systems, etc.. According to Soil Survey Division Staff (1998), soil moisture regime is *ustic* (soil moisture is limited, but is present when conditions are suitable for plant growth) and soil temperature regime is *mesic* (with a moderate or well-balanced supply of moisture, as normal in Mediterranean regions).

In 2009 a detailed soil survey (map scale 1:15,000) was carried out on all the vineyards of the farm (Costantini *et al.*, 2009), with the traditional method, based upon photointerpretation and field survey (Soil Survey Division Staff, 1993). Five of the Soil Typological Units (STUs) described in the farm, are present in the study area (Fig. 2):

1) TOR, Torricella soil: Typic Haplustept clayey-skeletal, mixed, mesic, superactive according to Soil Taxonomy; developed on Tertiary carbonate flysch. Torricella soil is clay-loamy

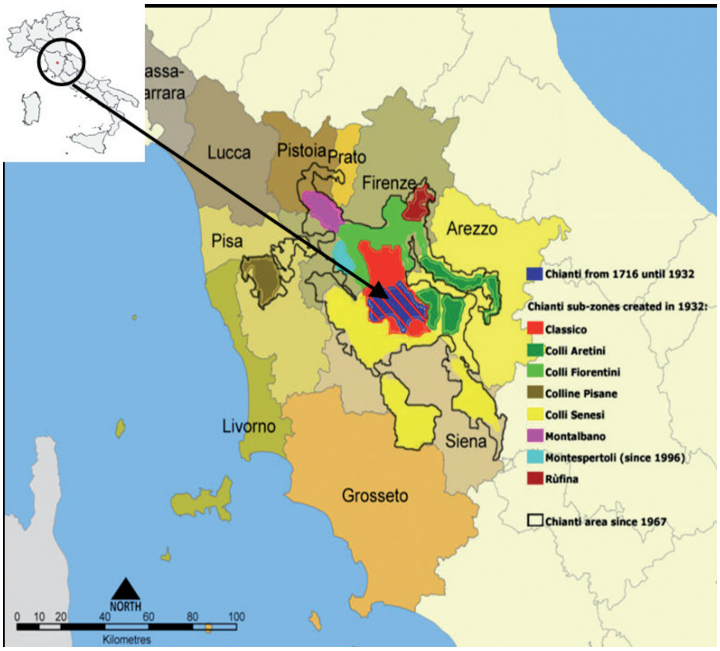

Fig. 1 - Geographical location of the studied area with evidence of the “Chianti Classico” wine district area.

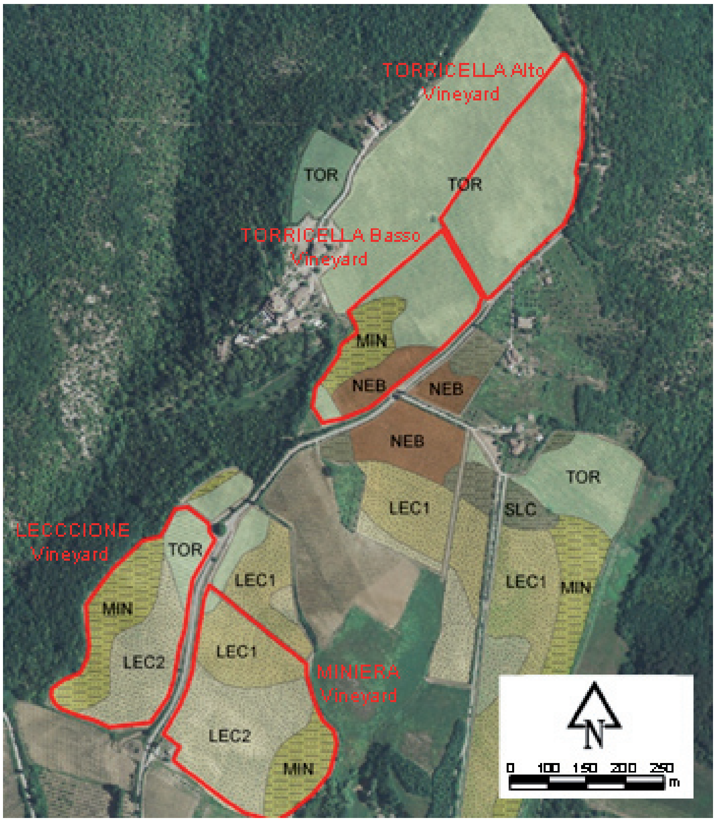

Fig. 2 - Pedological map of the studied area (modified from Costantini *et al*., 2009); in red the limits of the experimental vineyards.

and strongly gravelly, about 1.5 m deep, but it results poorly developed and with poor horizontation.

2) NEB, Nebbiano soil: Typic Paleustalfs loamy, mixed, mesic, superactive or Cutanic Luvisol (Hypereutric, Profondic, Clayic); developed on Pleistocene fluvial deposits, Nebbiano soil shows more developed pedogenesis. It is very deep (>1.5 m), loamy, with common fine and medium gravels, well structured.
3) LEC1, Leccio 1 soil: Typic Haplustalf fine-loamy over clayey, active or Hypereutri Cutanic Luvisol (Profondic); developed on Pliocene marine sand. Leccio 1 soil shows advanced pedogenesis and is very deep (>1.5 m), sandy-clay-loam, average structured and gravelly.
4) LEC2, Leccio 2 soil: Typic Haplustepts sandy or sandy-skeletal, active or Eutri Brunic Arenosol; represent a variant of the Leccio 1 soil and is less developed and highly eroded (thickness <1.5 m). The texture is sandy-loam and presents an excessive drainage.
5) MIN, Miniera soil: Typic Endoaquepts clayey, mixed mesic, superactive or Endogleyic Stagnosol (Eutric, Clayic); developed on Pliocene marine clays with some sandy-gravelly lenses. Miniera soil results poorly structured or massive, especially in depth (thickness <1.5 m), and very clayey (clay: 40-50%).

The soils TOR, LEC2 and MIN are classified as Inceptisols (suffix –ept), i.e. early-stage soils, not well developed, where the physical-chemical weathering of the parent material is dominant. The soils NEB and LEC1 are Alfisols (suffix –alf), i.e. are more developed and, after the weathering, hydrological processes drives to a movement (*lessivage*) of clay minerals toward deeper horizons.

2.2. Electromagnetic induction sensor and measurement procedure

The EMI instrument used for surface mapping of electric conductivity was the EM38-MK2 (Geonics Ltd., Ontario, Canada). The instrument consists of a transmitting coil and two receiver coils, spaced respectively 0.5 and 1.0 m from the transmitter. It measures the ECa at two depths at the same time for every measure location, using an operating frequency of 14.5 kHz. The physical principles behind the sensor functioning can be synthetized as follows: an alternating current flowing in a transmitting coil generates a primary magnetic field (Hp); the field creates an eddy current within the soil, which induces a secondary magnetic field (Hs), which is sensed, together with Hp, by the receiver coil. The secondary magnetic field and the depth of investigation are strongly related to intercoil spacing (s), operating frequency (f) and soil conductivity (σ). The ratio between Hs and Hp, providing to work under the low induction number approximation, is linearly proportional to the soil ECa (McNeill, 1980). The cumulative soil depth response of the instrument is a non-linear function and it is higher for the vertical dipole mode (VDP, coils perpendicular to the soil) respect to the horizontal dipole mode (HDP coils parallel to the soil). The measured data for the two dipole configuration have different sensibility response, which results, for the VDP, in a maximum sensibility corresponding to 0.25 and 0.50 m (respectively for the two intercoil spacing) and a maximum survey depth corresponding to 0.75 and 1.50 m (respectively for the two intercoil spacing).

The main advantage of the EMI instruments is that the induction principle does not require a direct contact with the ground. Consequently a survey carried out using EMI sensors can be faster than an equivalent survey carried out with other instruments. The survey can be performed by a single operator, while a GPS receiver, connected to the instrument, allows collecting georefered ECa data.

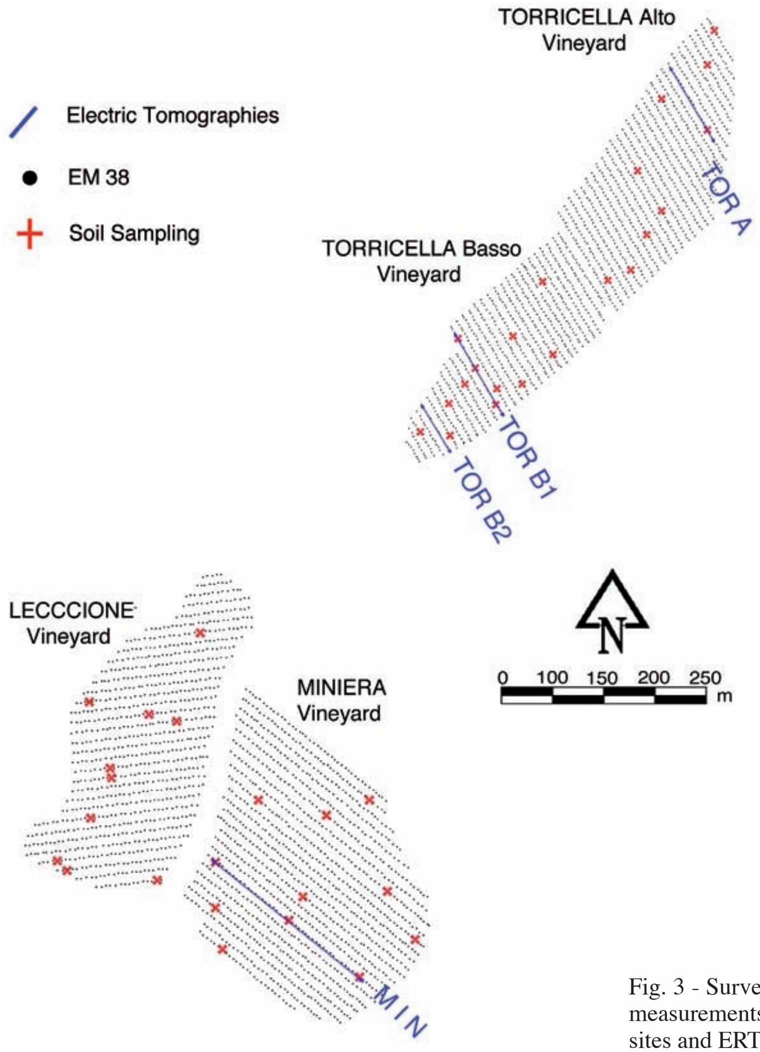

Fig. 3 - Surveys performed on the studied area: EMI measurements points, location of the soil sampling sites and ERT.

The EMI survey for the experimental area was carried out in VDP configuration, with a grid of 3x10 m (Fig. 3). For any vineyard, each survey was performed approximately at the same day time and all the area was covered within two weeks; at the beginning of each survey the sensor was calibrated in a selected site to minimize errors. Indeed a careful manual calibration is needed before the measurement procedure and, sometimes, interference of the iron wires of the vineyard rows with the magnetic field is possible. Geostatistical approaches are then necessary for data post-processing. This was performed by Ordinary Kriging with 1 m resolution. The final result of the EMI survey is therefore a regular grid of data points including ECa for two depths. These horizontal ECa maps, together with the pedological map were used as baseline data in the next steps of the work.

2.3. Soil sampling and laboratory analysis

After the EMI data spatialization, soil samples were collected to estimate the most relevant soil properties related to the soil ECa. On the basis of the ECa maps, 42 georefered sampling sites were selected and, for each location, two soil samples were collected at two different depths (respectively at 0-40 cm and 50-75 cm). Totally 72 hand auguring have been analysed (Fig. 3). Laboratory analyses were performed according to the Official Italian Methods (Mi.P.A.F., 2000) in order to determine: gravimetric water content (θg), soil reaction (pH), soil electrical conductivity and texture.

2.4. Electrical resistivity tomographies

Resistivity based methods measure the electrical resistivity, which can be transformed to its inverse, the electrical conductivity (EC), for a bulk volume of soil directly beneath the surface. Resistivity methods basically gather data on the subsurface electric field produced by the artificial application of electric current into the ground. In conventional methods, an electric current is supplied between two metal electrode stakes, partially inserted at the ground surface, while voltage is concurrently measured between a separate pair of metal electrode stakes also inserted at the surface. The current, voltage, electrode spacing, and electrode configuration are then used to calculate a bulk soil electrical resistivity (or conductivity) value (Allred *et al.*, 2008).

ERT were adopted in the study area to interpret vertical variations in EC along transects selected on the basis of the surface ECa distribution. The instrument used was Syscal Junior (IRIS Instruments, France) with 72 electrodes. Totally, 8 ERT were collected using Wenner-Schlumberger electrode arrays. Since the main interest of the surveys is the upper portion of soil profile a reduced spacing between the electrodes was used (1 m), for a total length of 71 m for each transect, to obtain an accurate near surface resolution. In some vineyards data from different transects were assembled, to obtain longer electrical sections (Fig. 3), with a roll along procedure and the overlap of some electrodes. The software RES2Dinv (Geotomo Software) was used for the inversion.

2.5. Selection of uniform sub-areas of wine making

In the final step of the work, a correlation between wine quality and soil features detected by pedological and geophysical methods was done. Homogeneous sub-areas within the vineyards were identified and separate wine-making were performed. For this purpose, a k-means cluster analysis was adopted using the software Statistica (StatSoft) and represented using ArcGIS (ESRI). Input data were:

- ECa values obtained by the EMI survey;
- ECa values obtained by a previous ARP survey (Automatic Resistivity Profile, Geocarta, France) in the summer 2009;
- AWC (Available Water Content) from pedological map;
- NDVI (Normalized Difference Vegetation Index) from satellite images (for two of the studied vineyards).

The cluster analysis was setup to obtain seven sub-areas, adopting Sangiovese as reference grape-variety. Within each of the zones the grapes were carried to the farm winery, where they were separately vinified using stainless steel tanks with a capacity of 95 hectolitres. The wines were analyzed to measure alcohol content (% vol), pH, total acidity (g l-1), dry extract (g l-1), color intensity (nm), total polyphenols (mg l-1), and total anthocyanins (mg l-1). Protocols for the

“Chianti Classico” wine request a minimum ageing of 2 years, to allow this wines should have suitable oenological characteristic. Relatively high values of alcohol (13-14%), antochyanins and polyphenols indicate prime conditions for wine ageing, therefore they are good indices of wine quality and ageing suitability.

4. Results and discussion

The detailed ECa maps of the four experimental vineyards obtained from the EMI survey are shown in Figs. 4 and 5 for the two intercoil spacing used; both maps, particularly the shallower one, are consistent with the pedological map shown in Fig. 2 and reflect soil variability in the area. Consequently we can state that the EMI survey could express well the pedological variability of the area and is able to highlight ECa patterns within the vineyards. A comparison with the results of the previous ARP investigation shows very similar patterns to the EMI survey demonstrating also the consistence of electrical methods in defining soil variability. Moreover, since ECa maps are an uniformly distributed sampling of the area a qualitative comparison between ECa maps and pedological map (as shown in Fig. 6) can suggests some changes in the STUs boundaries. However, detailed GPS-driven observations are needed to confirm the reliability of these changes. To further constrain these observations, as it will be shown below, the ERT can help to understand the geological and pedological assessment in depth.

The results of laboratory analysis were compared with the EMI survey data in order to establish a connection between the measured ECa and soil properties. To do this, for every soil sample, the respective ECa value was extracted from the EMI survey results. For the experimental vineyards it was possible to identify a coherent trend between ECa values and laboratory data (electrical conductivity of soil, clay content and water content). However the Pearson’s coefficient was not significantly high, as reported in Table 1. These results agree with what is widely reported

Table 1 - Pearson correlation coefficient (r^2) between clay content, gravimetric water content, estimated EC and measured EC.

r^2 MINIERA vineyard				
	clay	θg	EC_{lab}	EC_{EM38}
clay	/			
θg	0,65	/		
EC_{lab}	0,12	0,09	/	
EC_{EM38}	0,27	0,19	< 0,01	/

r^2 LECCIONE vineyard				
	clay	θg	EC_{lab}	EC_{EM38}
clay	/			
θg	0,89	/		
EC_{lab}	0,20	0,14	/	
EC_{EM38}	0,43	0,34	0,10	/

r^2 TORRICELLA *basso* vineyard				
	clay	θg	EC_{lab}	EC_{EM38}
clay	/			
θg	/	/		
EC_{lab}	/	0.06	/	
EC_{EM38}	0,12	0,11	0,06	/

r^2 TORRICELLA *alto* vineyard				
	clay	θg	EC_{lab}	EC_{EM38}
clay	/			
θg	0,17	/		
EC_{lab}	< 0,01	< 0,01	/	
EC_{EM38}	0,25	0,02	0,08	/

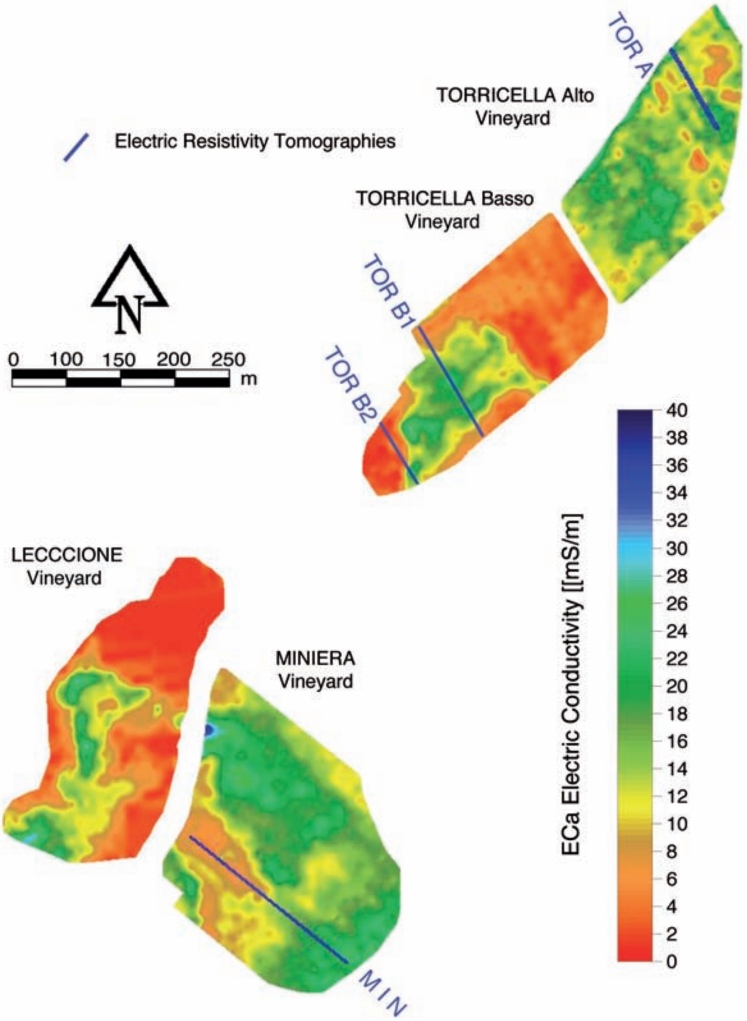

Fig. 4 - ECa maps as a result of the EMI survey for 0.5 m intercoil spacing.

in literature: ECa values are affected by various soil properties in a complex manner, and it is difficult to discriminate the weight that each soil parameter has on the final apparent measured ECa. Moreover, it must be observed that the volume investigated by the EMI survey and the one of localized sampling are quite different so that averaging processes could be relevant in the correlation. Note that clay content was determined only on the fine soil fraction ($\mu < 2$ mm), i.e. after removing the skeleton ($\mu > 2$ mm), in the aim of normalizing the texture: recent studies (e.g., Priori *et al.*, 2010c) have shown that clay content measured in this way is more consistent with the ECa measure of proximal sensing. Otherwise, the clay content would be underestimated for skeleton-rich samples, and overestimated for skeleton-poor samples. The grain size distribution curves, on the fine soil fraction, for the five STUs of this study are reported in Fig. 7: it is possible to observe the different fine fraction content of each soil which affect both the geophysical and the pedological characterization, having an influence on wine production, as it will be underlined later.

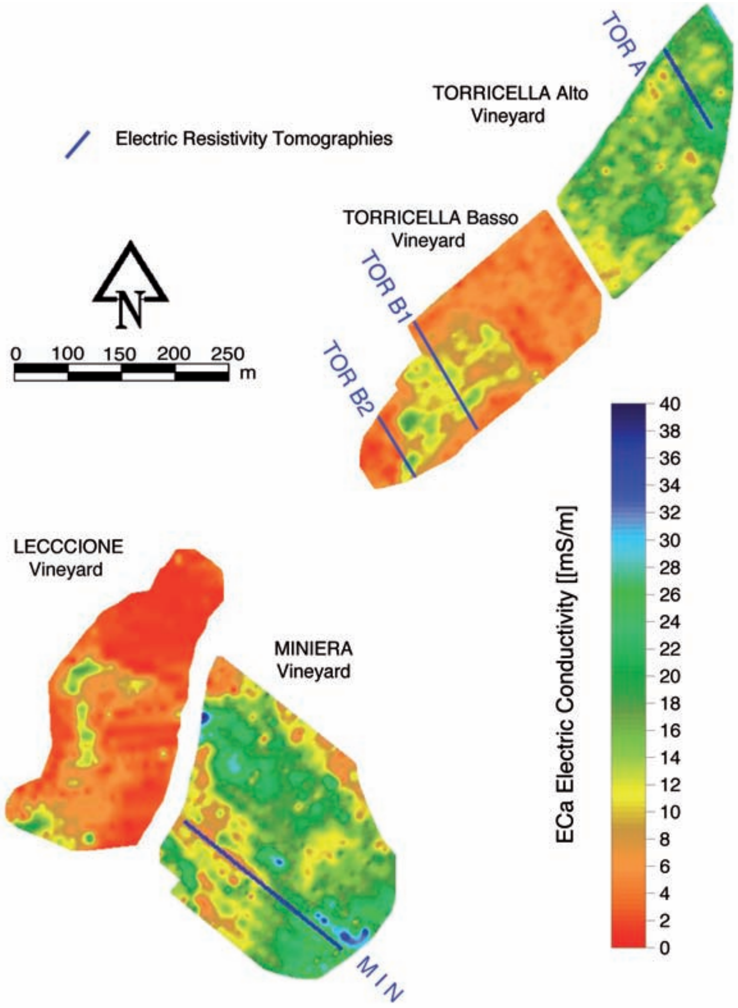

Fig. 5 - ECa maps as a result of the EMI survey for 1 m intercoil spacing.

High resolution ERT sections were obtained in different STUs, focusing on the upper portion of the soil profile. Fig. 8 shows the results of the three most interesting sections. Results are reported in term of electrical conductivity data for a consistent comparison with ECa maps and at different scales to focus on the peculiar aspects of each section. In all situations there is a very good coherence in the determination of the different soil boundaries.

The MIN section (Fig. 8a) clearly evidences the geological contact between sandy and clayey formations. It is particular detailed the transition from LEC2 sandy-loam soil, on top of the slope, and the MIN clayey soil on the bottom of the slope. Moreover, it is interesting to observe a conductive anomaly in the upper part of the slope (at the progressive of 50 m), that corresponds to a humid zone observed in the soil surface and underlined also by the ECa map, representing a preferentially drainage direction. We can suppose that this feature may produce instability phenomena along the slope consequently to wet season and affect grape yield and must quality.

The TOR B2 section (Fig. 8b) clearly shows the geological contact between different units, leading to relative differences in soil ECa. Indeed, in the right side of the section, a high

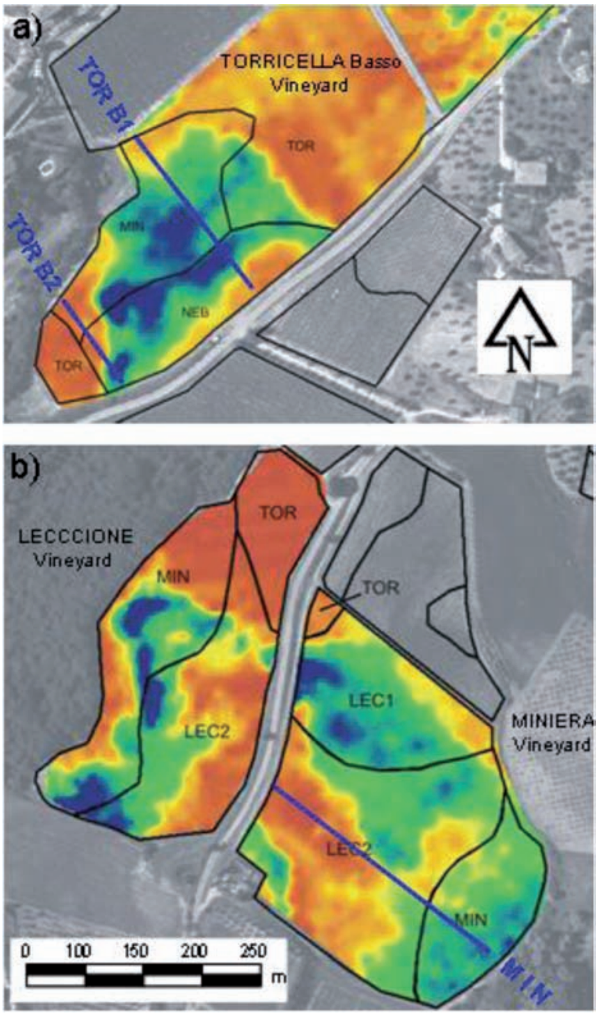

Fig. 6 - Comparison between STU boundaries and ECa map: a) detailed view of the Torricella Basso vineyard; b) Leccione and Miniera vineyards; the location of electric tomographies is also shown.

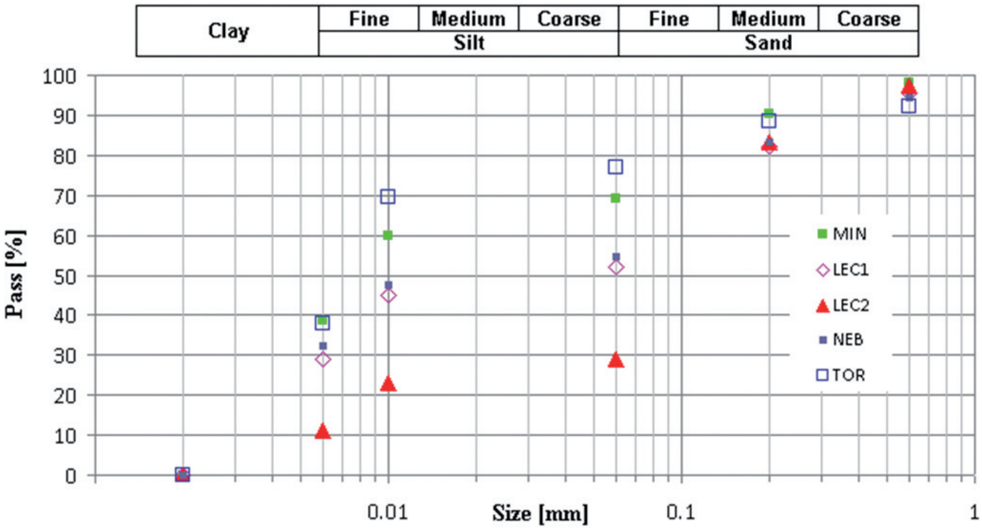

Fig. 7 - Grain size distribution curves on the fine soil fraction for the five STUs of this study.

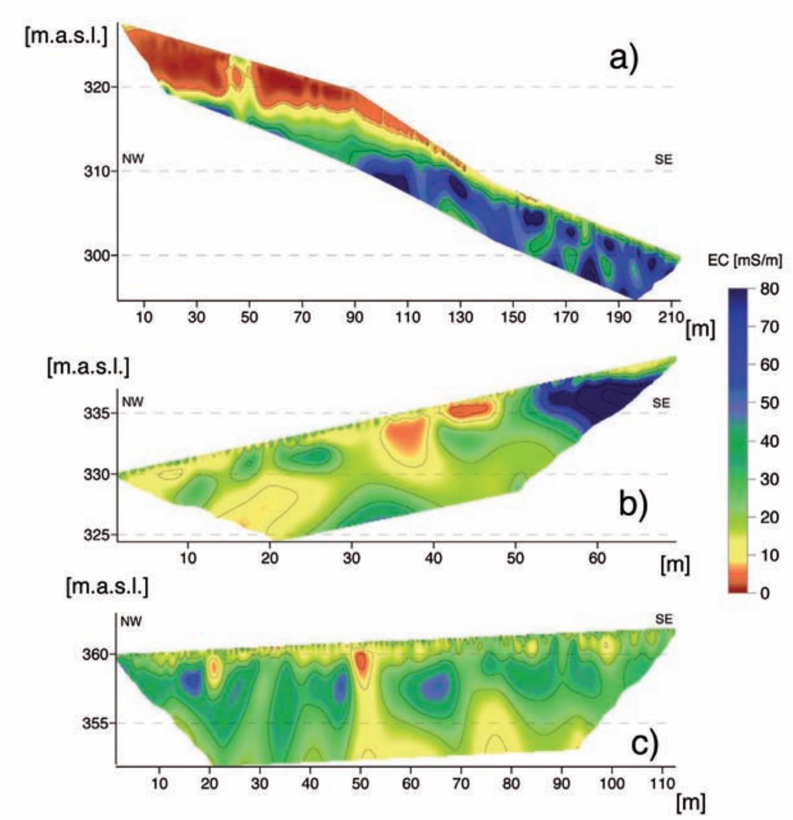

Fig. 8 - Inverted ERT sections, please note the different scales: a) Miniera vineyard (MIN); b) Torricella Basso vineyard (TOR B2) and c) Torricella Alto vineyard (TOR A).

conductivity clayey soil is observed delineating a zone of the subsection which evidences the presence of a sedimentation basin sloping toward SE. The low conductivity anomalies in the left side of the section are typical of the flysch formation. The high consistence with the ECa map in evidencing the boundary between TOR and NEB soils confirms that the boundaries in the soil map are somehow incorrect, and need changes as evidenced in Fig. 6.

The TOR A section (Fig. 8c) is located on a uniform and resistive soil (Torricella STU) so that this result is not particularly interesting from a pedological point of view. However, two highly restive anomalies are evident at the progressive distances of 20 and 50 m respectively, corresponding to two dry drainage pipes. This observation was helpful for the farm holders in order to verify their location and effectiveness.

Finally, in Fig. 9, the Normalized Difference Vegetation Index (NDVI) map extrapolated from a multi-spectral image of the Kompsat-2 satellite (resolution of 4 m), is reported. The map refers to the Torricella vineyards and was taken during the same maturation season in which the other geophysical tests were performed (August 2010). It is interesting to note that nevertheless these vineyards are characterized by a quite uniform soil distribution similar patterns can be observed both in the NDVI map and in the ECa map. Once again this is a confirmation of the potentiality of the EMI survey for precision agriculture scopes.

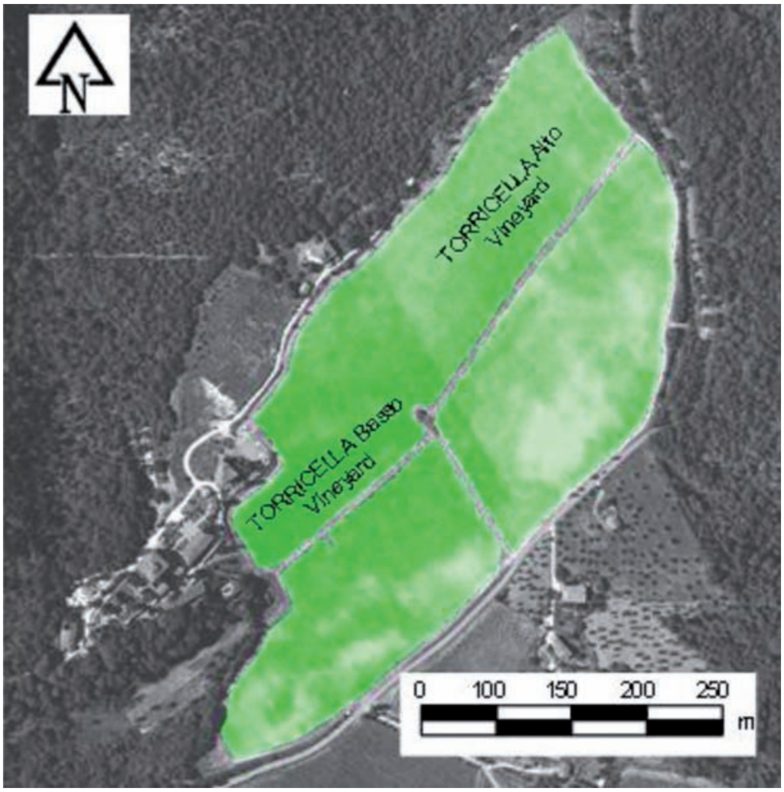

Fig. 9 - NDVI map of Torricella vineyards.

5. Wine-making areas and wine quality

The cluster analysis combining geophysical, pedological and remote sensing data was setup to obtain seven sub-areas, adopting Sangiovese as reference grape-variety. It was underlined that the EMI survey maps have the strongest influence in clustering. The sub-areas geometries resulting from the cluster analysis were however too complex. For this reason, to make the proposed methodology easily manageable in practical terms, the boundaries of the sub-areas were manually modified (e.g., to make them parallel to the directions of the rows). The resulting map is shown in Fig. 10.

The seven resulting sub-areas, corresponding to a combination of pedological and geophysical features, are:

- sub-area 1: Pliocene sands (Miniera and Leccione vineyards);
- sub-area 2: Pliocene clays and Leccio 1 soils (Miniera and Leccione vineyards);
- sub-area 3: Tertiary flysch and Leccio 1 soils (Miniera and Leccione vineyards);
- sub-area 4: Pliocene clays (Torricella vineyard);
- sub-area 5: Tertiary flysch and Nebbiano soils (Torricella vineyard);
- sub-area 6: Resistive Tertiary flysch (Torricella vineyard);
- sub-area 7: Conductive Tertiary flysch (Torricella vineyard).

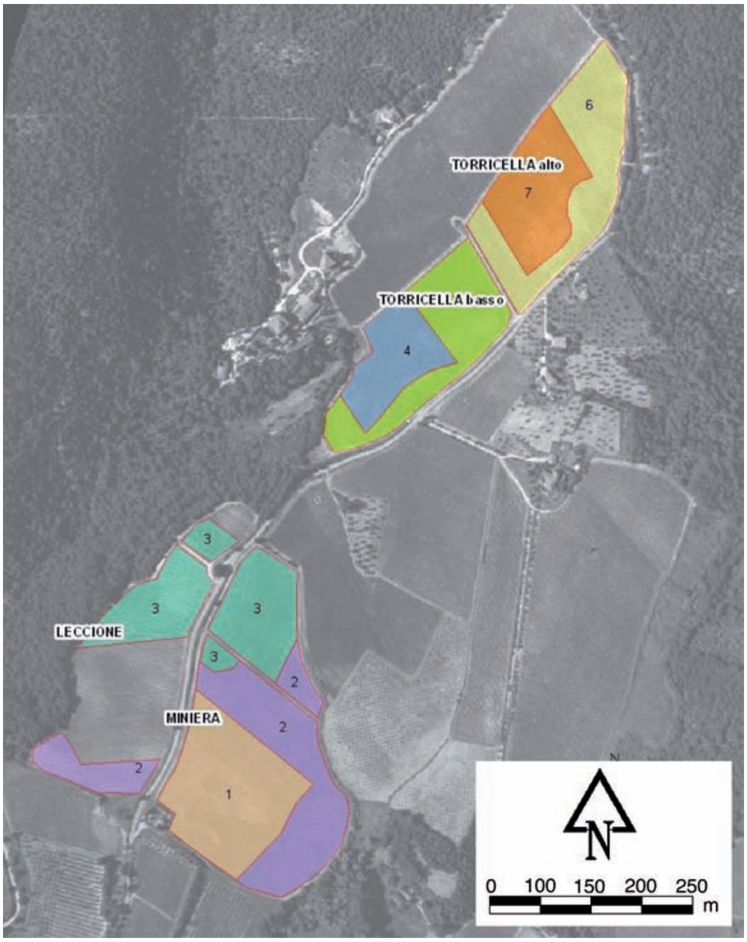

Fig. 10 - Wine-making areas map, manually modified.

It is worthy note that sub-areas 6 and 7, both belonging on the same STU, were separated only by different electrical properties. Grapes from sub-areas were harvested separately and everyone produced a wine, then analyzed by the "Barone Ricasoli" farm. Wine made from any sub-area of wine-making shown all excellent quality. Indeed, the Chianti Classico district is strongly suited to the Sangiovese grapes production. Moreover, it must be underlined that the management of grapes during the ripening and the harvesting influenced the results in terms of quantity and quality: only good quality grapes were harvested, leaving on the plants the grapes interested by Botrytis Cinerea (a fungus that affects the grapes and was particularly widespread in that year). Due to that, in sub-areas 2 and 4 (developed on clayey soils and located at the bottom of the slopes, therefore more humid) the production was reduced of about 50% in quantity and result in lowest quality with reference to the other wines. Sub-area 2 in particular is the one where this effect was predominant; indeed, the results of geophysical tests conducted in this zone of the vineyards underlined the presence of highly conductive clayey soils that could have the greatest water retention (Figs. 4, 5 and 8a). This water retention was the main cause for the increased presence of Botrytis Cinerea on these areas. As result of this practice, grapes quality was "artificially" improved, and the differences between grapes from different sub-areas were furthermore minimized. Although,

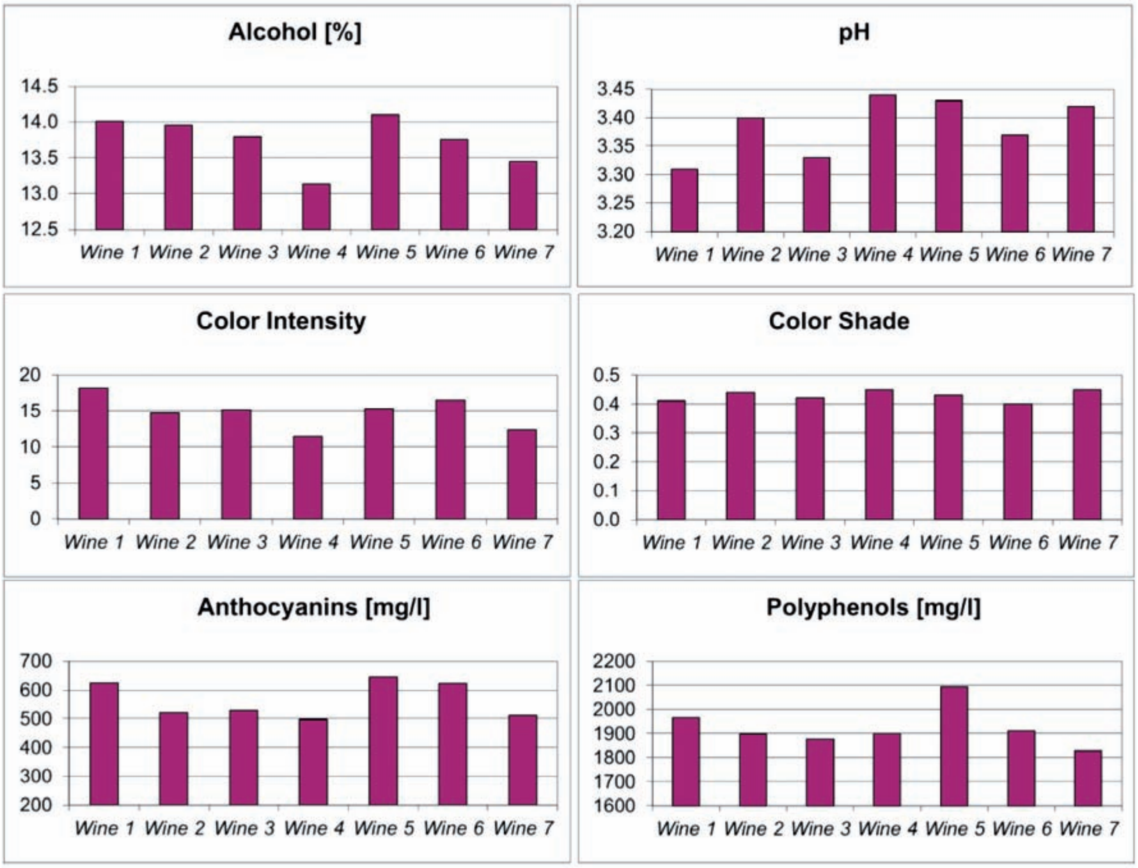

Fig. 11 - Oenological parameters comparison: the wines 1-7 have been produced by the seven sub-areas of wine-making of Fig. 9.

differences in some oenological parameters (color intensity, dry extract, alcohol, anthocyanins) and taste peculiarities were found between the sub-areas (Fig. 11). What is particularly interesting are the differences observed between sub-areas 6 and 7 which, as mentioned, were differentiated only on the basis of electric conductivity.

6. Conclusions

An integrated methodology is proposed, allowing minimizing errors and obtaining ECa maps with good resolution and able to show the soil horizontal variability in electrical properties. ECa maps resulted very similar to other maps obtained by EMI and geoelectrical surveys in previous studies in the same vineyards. This outcome confirmed that i) soil ECa is substantially constant in time, depending on the lateral variations in soil properties (Lund *et al.*, 1999; Allred *et al.*, 2006) and ii) well correlated ECa values can be measured by EMI and geoelectrical instruments (Sudduth *et al.*, 2003; Priori *et al.*, 2010a, 2010b), producing similar maps (Doolittle *et al.*, 2002; Priori *et al.*, 2010a, 2010b).

ERT allowed to obtain further information, otherwise non achievable by the EMI survey, although EMI survey is more suitable than ERT to express soil variability. In detail, electrical sections can be very useful to understand geological asset, to detect and monitor underground drainage systems and to recognize particular structures that can induce geotechnical problems.

Geophysical-pedological combined survey techniques can help in understanding the STU boundaries. On the other hand, the pedological survey cannot be fully replaced by non-invasive methods, which can only represent a support for agricultural aims. Moreover, measured ECa was poorly correlated to soil functional properties, in as much as a simple EMI survey could not provide a soil properties estimate, although the geophysical study allowed a more complete and fast assessment of soil spatial variability.

For the viticultural application, in all phases of the work an objective criteria has been adopted to make any step reproducible. In conclusion, the proposed methodology is suitable to identify areas with different production potential.

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Corresponding author: Edoardo Martini
Department of Monitoring and Exploration Technologies
Helmholtz Centre for Environmental Research – UFZ
Permoserstraße 15, 04318 Leipzig, Germany
Phone: +49 3412351038; fax +49 34123451038; e-mail: edoardo.martini@ufz.de